Integrated spatial and spectral characterisation of harmful algal blooms in Dutch coastal waters (ISCHA)

van der Woerd, H.J.; Blauw, A.; Pasterkamp, R.; Tatman, S.; Laanen, M.L.; Peperzak, L.

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Demonstration of a HAB service in the Zeeuwse Voordelta

H. J. van der Woerd	IVM/VU
A. Blauw	WL/Delft Hydraulics
R. Pasterkamp	IVM/VU
S. Tatman	WL/Delft Hydraulics (Geomatica Park)
M. Laanen	Water Insight
L. Peperzak	RIKZ

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IVM

Institute for Environmental Studies
Vrije Universiteit
De Boelelaan 1087
1081 HV Amsterdam
The Netherlands

Tel. ++31-20-5989 555
Fax. ++31-20-5989 553
E-mail: info@ivm.falw.vu.nl

A false colour image of Zeeland. This image was acquired on September 24, 2002, by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on NASA's Terra satellite. It shows in detail (20 meter resolution) the study area and the complexity of the hydrodynamic flow near the coast.

Project partners

Rijkswaterstaat RijksInstituut voor Kust en Zee/RIKZ

WL | delft hydraulics

Institute for Environmental Studies/ Vrije Universiteit

Water Insight BV

P.O. Box 35

2600 AA Delft

The Netherlands

Kluyverweg 1

2629 HS Delft

The Netherlands

Tel. +31 (0)15 278 80 25

Fax +31 (0)15 262 30 96

NATIONAL USER SUPPORT PROGRAMME (NUSP)

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The National User Support Programme 2001-2005 (NUSP) is executed by the Netherlands Agency for Aerospace Programmes (NIVR) and the SRON Netherlands Institute for Space Research. The NUSP is financed from the national space budget. The NUSP subsidy arrangement contributes to the development of new applications and policy-supporting research, institutional use and use by private companies.

The objectives of the NUSP are:

- To support those in the Netherlands, who are users of information from existing and future European and non-European earth observation systems in the development of new applications for scientific research, industrial and policy research and operational use;
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- To assist in the development of a national Geo-spatial data and information infrastructure, in association with European and non-European infrastructures, based on Dutch user needs;
- To supply information to the general public on national and international space-based geo-information applications, new developments and scientific research results.

Contents

Abstract

Phaeocystis globosa blooms in The Netherlands can cause damage to the ecosystem and commercial shellfish by producing benthic anoxia. In the past years the Dutch early warning system relied on samples from three coastal stations in which *P. globosa* cells were counted. Integrated Spatial and spectral Characterisation of Harmful Algal blooms in Dutch coastal waters (ISCHA) is a new project that uses, in addition to the in-situ measurements, chlorophyll-a maps derived from a satellite spectrometer (MERIS). High levels of Chlorophyll-a in the Voordelta in spring are indicative of the development of a HAB. The observations are compared to the outcome of the GEM coupled algal growth and transport models to investigate if growth conditions for *Phaeocystis globosa* are favourable. Using weather forecasts the development of the *Phaeocystis* bloom and its transport to coastal areas that are vulnerable to anoxia are calculated so that local water managers and shellfish growers can be notified in advance with a 'HAB-bulletin'.

The outcome of this project is a prototype system that combines near-real-time monitoring with remote sensing plus field data and real-time forecasting with the model. The system is demonstrated in hindcast for the year 2003.

The *Phaeocystis globosa* abundance and chlorophyll-a concentrations in 2003 observed by field monitoring were well reproduced by both the GEM model and the MERIS remote sensing images. By combining data from three different sources of information in the early warning service, optimal use can be made of the reliability and coverage in space and time of the different data, offering much more robustness than the traditional monitoring practice. From an economical point of view the service can be offered at competitive prices, compared to the existing in-situ monitoring. The ISCHA service can be an important tool to improve early warnings that will enable mitigation of the negative aspects of HAB for the Dutch mariculture.

1. Introduction

High biomass algal blooms can have a strong negative impact on fisheries, recreation and public health. In the Dutch Oosterschelde tidal inlet for example mass mussel mortality occurred in 2001 after an algal bloom flushed in from coastal waters. Similarly, algal blooms by cyanobacteria in fresh water can form nuisance scum layers and be toxic to humans, waterfowl and domestic animals.

These high-biomass blooms are linked to eutrophication. In nutrient-poor fresh waters algal blooms do not occur. Blooms always occur during summer when water temperature is high. Coastal blooms of the algal species *Phaeocystis globosa* have also been associated with eutrophication. The projected changes in precipitation in North-West Europe, as a result from climate change, will induce enhanced water and nutrient supplies to the coastal area. Increases in algal blooms are therefore expected as the result of increased river run-off in winter and spring.

Recent results from the HABES project (Harmful Algal Blooms Expert System (Blauw *et al*., 2004, Blauw *et al*., accepted) strongly pointed out that many harmful algal events result from algal blooms originating off-shore being transported to near-shore waters like beaches, embayment with aquaculture, intakes for drinking water, marinas etc. where they can cause harm. Therefore, reliable predictions of such harmful algal events would be possible if the location of an offshore bloom can be observed with remote sensing and if a transport model can predict the transport of this bloom. Predictions on the transport of blooms to near-shore waters can be made in various ways, ranging from coarse predictions based on the expected averaged wind conditions, to sophisticated predictions using weather forecasts from meteorological models.

Detection of elevated chlorophyll levels and bloom characterisation (dimension, growth, transport) derived from satellite data are a promising new form of information. Remote sensing can detect the spatial and temporal evolution of biomass, albeit without explicit information on species or the toxicity. Recently the REVAMP (Regional Validation of MERIS chlorophyll Products in the North Sea) project demonstrated that validated MERIS (Medium Resolution Imaging Spectrometer) chlorophyll-a products in North Sea coastal waters can be retrieved with unprecedented accuracy (see Peters *et al*., 2005).

However, the use of remote sensing information has so far been hampered by the late availability of these data to water managers. Usually remote sensing images only become available after the harmful algal event has passed. New developments related to the GMES (Global Monitoring for Environment and Security) initiative of the European Commission (EC) and the European Space Agency (ESA) have eliminated this problem; MERIS data are available within 24 hours from the COASTWATCH and MARCOAST ESA GSE projects (www.esa.int).

When combined with field data, the combination of remote sensing images and models would give valuable information on causes and trends of high-biomass harmful algal blooms. Typically these three data sources can reveal only part of the information required to understand the dynamics of the blooms. Field observations give a relatively reliable estimate of concentrations of algae in the water. However, the observations are made only at a relatively low number of locations on few occasions. Remote sensing pictures have a good spatial and temporal coverage, provided that cloud coverage is limited. However, the quantitative estimates are less reliable than field measurements. Models simulating algal growth have a complete spatial and temporal coverage, as they simulate algal concentrations on every time of the day and on every location in the model area. Furthermore, models give information on cause-effect relations and they can make predictions for the future. However, the reliability of the simulation results should always be tested and thus depends strongly on the level of validation with observed data, from either field observations or remote sensing images.

The ISCHA project covers an essential step to include Earth Observation data in an early warning system for development and fate of harmful algal blooms (HAB). The aim of this project is to fully exploit the observation of algal blooms with the MERIS instrument on the European ENVISAT. The high-resolution maps derived from MERIS are processed and combined with in-situ measurements and Harmful Algal growth models in order to produce timely information with the highest possible quality control.

In this project a pre-operational domain-specific application will be developed. This specific area in the Netherlands will cover the ‘Voordelta’ coastal area. It will focus on a hindcast simulation of April-May 2003 when a major bloom was observed (in-situ and from satellites).

This report covers the major outcomes of the project. First, in chapter 2 more background is given on the problem of the spring bloom of *Phaeocystis globosa* in the Voordelta. In Chapter 3 the requirements of an early warning system are defined. In chapters 4 and 5 the building blocks of the service are described. The outcome of the hindcast exercise for spring 2003 is presented in chapter 6. Here the outcome is also evaluated and compared to the requirements defined in Chapter 3.

The last chapters are related to the prospects of the ISCHA HAB service and the HAB bulletin. In Chapter 7 a SWOT analysis is carried out to advise on the feasibility of an integrated HAB early warning service for the Voordelta, i.e. the ISCHA service. A cost-benefit analysis has been performed to give an overview of the costs and benefits if the service is continued in the future. Finally, in Chapter 8, the most important aspects are summarized.

2. Problem Definition and Study Area

2.1 Harmful Algal Bloom (HAB)

A harmful algal bloom is defined as a proliferation of algae to the extant that harmful, noxious, deleterious or mortal effects on other biota become apparent. Several species of harmful algae produce some kind of chemical that is directly harmful to zooplankton, fish or mammals. The toxins of other harmful algal species may be concentrated in shellfish tissue and the effect of those toxins may become apparent only after consumption of that tissue. A third group of harmful algae do not produce toxins but, because their blooms attain a very high biomass, they exert a strong negative impact via oxygen depletion during bloom decline. One such high biomass species is the prymnesiophyte Phaeocystis globosa. Because P. globosa is the main phytoplankton component in spring blooms in Dutch coastal waters, its bloom development needs not be measured by cell counts. Instead CHLa can be used as a proxy for P. globosa biomass. A more detailed account of the occurrence of HABs near the Dutch North Sea can be found in Peperzak (1994).

2.2 The Voordelta

The southern North Sea is one of the most eutrophied marine systems in the world. Large rivers such as the Rhine and Meuse and other smaller rivers discharge in a relatively shallow shelf sea, enclosed between the United Kingdom and continental Europe. Although the area is naturally rich in nutrients, eutrophication has increased considerably during the 20th century, due to anthropogenic inputs (Van Bennekom et. al 1975, Peeters and Peperzak, 1990). There is concern about negative ecological impacts due to eutrophication such as the increased intensity and frequency of *Phaeocystis* blooms (Cadée and Hegeman, 2002, Riegmann *et al*., 1992).

The Voordelta is a complex system where many different water masses meet. In Figure 2.1 below the lower part of the graph (South of the Noordwijk transect) near the coast of Zuid-Holland and Zeeland indicates our study area. The black dots indicate the position of in-situ measuring stations of Rijkswaterstaat.

2.3 Past HAB events

During the spring bloom in 2001 strong northerly winds reversed the normal direction of the freshwater Rhine plume, in which a Phaeocystis bloom developed. In other words, this Phaeocystis-plume extended towards the south and entered Lake Grevelingen and the Oosterschelde. Entering of the bloom into Lake Grevelingen was noticed because surface waters at the lake entrance, a sluice, were monitored for Phaeocystis. Shortly after the bloom had entered, the lower half of the water column became oxygen depleted most probably the result of the decaying high Phaeocystis biomass. Presumably, the same scenario occurred in the Oosterschelde, leading to a €20 million loss of cultured mussels (Mytilus edulis). The reversal of the Rhine plume direction under the influence of wind is well known from model simulations of the Voordelta (De Kok, 1996) and, therefore, this process is amenable to model predictions once meteorological forecasts and river run-off predictions are available.

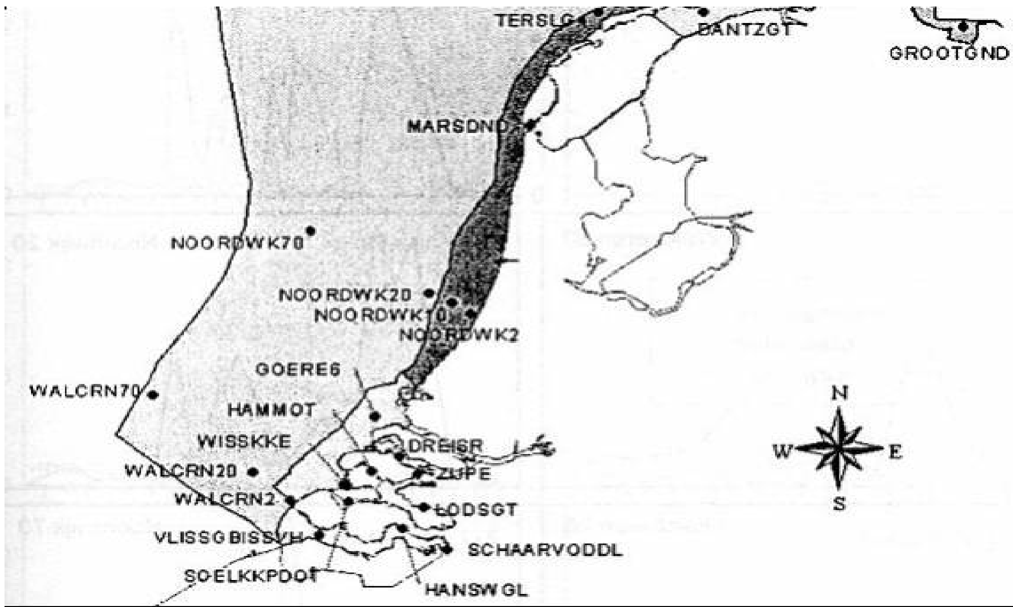

Figure 2.1 The Southern Bight of the North Sea near the Dutch coast ('Voordelta').

2.4 Future HAB events

The magnitude of the Phaeocystis spring bloom in the southern North Sea is most probably related to cultural eutrophication, i.e. the man-induced increase in plant the nutrients nitrogen and phosphorus. Although nutrient concentrations in the Rhine, notably phosphorus, have declined in the 1980s, their concentrations are still not considered acceptably low. Furthermore, in years with heavy rainfall as in 2001, the nutrient flux out of the Rhine (nutrient concentration x flow rate) increases and, theoretically, enhances the magnitude of the Phaeocystis bloom. In 2001 for instance, Phaeocystis bloom development stopped after the phosphate concentration in the Rhine had declined to near zero values. Very likely bloom events are here to stay, not in the least by the climate changes that are expected in the coming years to centuries. The projected changes in precipitation patterns in North-West Europe, as a result from climate change, will induce enhanced water and nutrient supply in winter to the coastal area. Increase in algal blooms is therefore expected as the result of increased river run-off in winter and spring, although the increase may depend on species and season (Peperzak, 2003).

3. Methods

3.1 The MERIS Chlorophyll-a data

In The Netherlands, several demonstration projects have shown that remote sensing is a useful source of information on water quality in the North Sea. A good example is the production of yearly atlases of total suspended matter based on SeaWiFS imagery (Pasterkamp *et al.*, 2001; Pasterkamp *et al.*, 2003). More recently, the European project REVAMP (Peters *et al.*, 2005) has shown that images from the MEdium Resolution Imaging Spectrometer Instrument (MERIS) can be validated with in situ measurements and can produce maps of chlorophyll-a concentration for the North Sea.

In ISCHA and in the AAN (Algen Atlas Noordzee) project a new regional (Dutch continental shelf) algorithm ('HYDROPT') was developed that simultaneously retrieves TSM and CHL from observed reflectance spectra and gives an estimate of the retrieval accuracy. (Pasterkamp *et al.*, in preparation).

The sea spectral reflectance (SSR) measured by satellite ('ocean colour') is linked to the optical properties of the sea, i.e. absorption a and scattering b. The constituents in the water, in turn, determine these optical properties. The basic challenge of each remote sensing algorithm is to calculate the concentrations of these optically active constituents from the measured sea spectral reflectance. The approach of the algorithm presented here (called 'HYDROPT') is to iteratively adjust the concentrations by minimizing the difference between a measured reflectance spectrum and the reflectance spectrum generated by a forward model. Detailed description and rationale for this method will be published in an article, which is still in preparation. Here we will restrict ourselves to a short explanation that is divided in two parts: the description of the forward model, and the description of the inverse method (See also Pasterkamp *et al.*, 2005).

The forward model calculates the sea spectral reflectance ($R_{rs}(\lambda)$) given the concentrations (see Fig. 1). Here the model is based on output of the Hydrolight radiative transfer code (see http://www.sequoiasci.com/products/Hydrolight.aspx). Hydrolight is a well documented (Mobley, 1994) numerical solution of the radiative transfer equation, and is known for its accuracy (Mobley *et al.*, 1993) and flexibility.

A drawback is that the model takes too much computational time to make it suitable for real-time satellite processing (this is a general drawback of numerical models as compared to analytical approximations such as the equations proposed by Gordon (1975). To bypass this problem, the output of the forward model was approximated by a polynomial function, which evaluates much faster than the full numerical model. The forward model is defined as the remote sensing reflectance (a quantity that depends on observation geometry) as a function of inherent optical properties absorption a and scattering b. Testing with random sets of absorption and scattering shows that the polynomial approximation replicates the original Hydrolight output within 2% (averaged over all geometries, absorption and scattering coefficients and wavelength).

The use of absorption and scattering as independent variables instead of the concentrations has the advantage that conversion of concentrations to optical properties remains outside the model. As a result, this conversion can be defined on a regional or even pixel-by-pixel basis without the need to run Hydrolight or recalculate the polynomial coefficients. To retain the angular dependence of the remote sensing reflectance, and to include the pure water volume scattering function for each wavelength, the polynomial coefficients are computed and stored for each combination of MERIS-wavelength, solar zenith, viewing zenith and differential azimuth angle (see Hydrolight documentation for the definition of so-called quads).

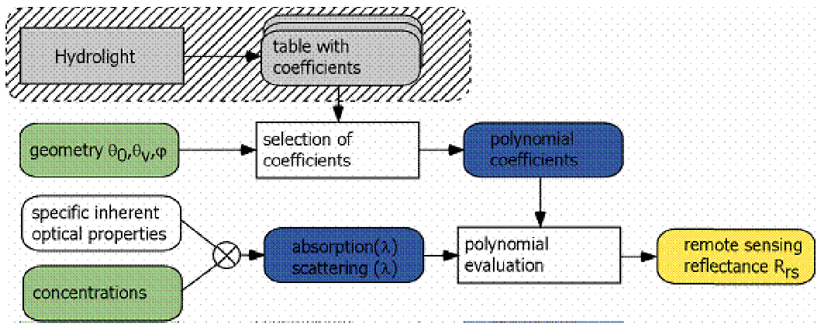

Figure 3.1 Illustration of the forward model.

The goal of the inverse method is to reverse the calculation of the forward model, i.e. to calculate the concentrations from the sea spectral reflectance. The inversion of the forward model is accomplished here by fitting the modelled remote sensing reflectance to a measured reflectance spectrum, while varying the concentrations (see Fig. 3.2). The 'best-fit' concentrations belonging to the minimum difference are then assumed to be the most likely concentrations corresponding to the measured spectrum.

Because the remote sensing reflectance is a nonlinear function of concentrations, a nonlinear optimization method was implemented, originally published by Levenberg and Marquard (Levenberg, 1944). This method was selected because it is well established, fast and reliable. The method also gives the standard errors in the fitted concentrations. These errors can be presented to end-users (in addition to general validation with in situ measurements) as a pixel-by-pixel estimate of accuracy.

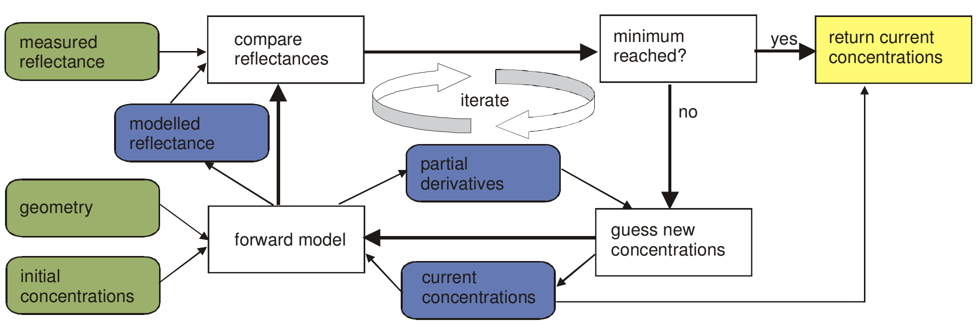

Figure 3.2 Scheme of the inversion and retrieval process.

The specific inherent optical properties (SIOP) are defined as the absorption or scattering per unit concentration of a certain constituent. Accurate knowledge of the optical properties of dissolved and particulate matter in water is essential, because they constitute the physical link between remote sensing reflectance and the constituents' concentrations.

Unfortunately, these optical properties can change with location and time. Bricaud *et al.* (1995) observed that the chlorophyll *a*-specific absorption coefficients of living phytoplankton decreased over 1 order of magnitude from oligotrophic to eutrophic waters. This variation was confirmed by Babin *et al*. (2003b), who, in addition, found that 'phaeopigment concentrations in coastal waters may lead to [even] larger and unpredictable variations.' Babin also reported variations in the absorption properties of coloured dissolved organic matter and non-algal particles (Babin *et al*., 2003b) and in the scattering properties of marine particles (Babin *et al*., 2003a). As a consequence, the variations of optical properties in our study area should be analyzed in detail, and an error analysis should be conducted to estimate the effect of the variability on the accuracy.

Because of the complexity of the North Sea system (currents, light limitation, sediment origin), especially along the coast (riverine input, resuspension), it is difficult to parameterise an optical model with locally measured optical properties alone. As an alternative, we have parameterised a single optical model that performs optimal for the Dutch coastal zone, by optimizing the validation with in situ measurements (see next paragraphs) until a minimum root-mean-square-difference was found. A three-component model (chlorophyll-a, total suspended matter, coloured dissolved organic matter (CDOM)) was thought to be sufficient to explain the optical domain of the North Sea without creating overlapping SIOP ('overtraining'). The solution space was further limited by fixing the spectral function of absorption of bleached particulate matter and the absorption of dissolved matter to an exponential function (with varying slope), and setting the scattering of CDOM and CHL to zero. Further explanation of this method will be published as soon as possible. The optimized coefficients of the optical model are presented in Table 3.1.

Table 3.1 Coefficients of the optical model specified for MERIS wavelengths.

	Absorption				Scattering	
Wavelength	pure water	chl-a specific	tsm-specific	cdom-normalised	pure water	tsm-specific
Nm	m^{-1}	m^2mg^{-1}	m^2g^{-1}	1	m^{-1}	m^2g^{-1}
412.7	0.007	0.022	0.034	1.117	0.007	0.411
442.6	0.011	0.039	0.027	0.992	0.005	0.426
489.9	0.018	0.026	0.019	0.820	0.003	0.335
509.8	0.033	0.028	0.016	0.758	0.003	0.386
559.7	0.067	0.009	0.011	0.621	0.002	0.346
619.6	0.281	0.009	0.007	0.490	0.001	0.293
664.6	0.399	0.046	0.005	0.410	0.001	0.345
708.3	0.706	0.000	0.004	0.350	0.001	0.262

The accuracy of the outcome of the algorithm is assessed by comparing MERIS data and time series instead of single measurements for the Dutch monitoring stations. By looking at time series, random differences introduced by scale dissimilarity and a-synchronous sampling will, to a certain extent, be averaged out (the more measurements, the better), and systematic offsets can be investigated. Another option is look at the seasonal patterns in chlorophyll-a and total suspended matter concentration at the monitoring stations. Again, sufficient data points are needed to make a meaningful comparison. In both cases, pixels were extracted from the MERIS level 2 imagery (reflectance) at the location of the monitoring stations (nearest neighbour interpolation) and processed with the HYDROPT algorithm to give chlorophyll-a and total suspended matter concentrations.

The level 2 MERIS data consists of all reduced resolution data covering the Dutch coastal and marine zone in 2003, and was acquired in the REVAMP project. The level 2 version is equal to the first MERIS reprocessing. In 2003 an average of 38 cloud-free and good-quality MERIS observations was available for each station.

The results of the analysis of yearly geometric means for Dutch monitoring stations are shown in Figure 3.3. The green squares represent the yearly geometric mean (labelled 'median', because the geometric mean is an estimator for median when the underlying distribution is log-normal) for chlorophyll-a for each measurement station. The relative root-mean square difference (RMS) between remote sensing and in-situ is 15%, with a correlation coefficient of 0.97. Part of this difference can be attributed to the statistical uncertainty in the geometric mean. This exercise shows the lack of systematic offsets between both datasets, as algorithm performs well for low and high ranges of chlorophyll-a. Considering the fact the RMS includes the effect of atmospheric correction errors, scale differences and temporal differences (i.e. the temporal distribution of measurement over the year for in situ and remote sensing can be slightly different), the effective RMS error of 15% is probably the best that can be achieved under these circumstances.

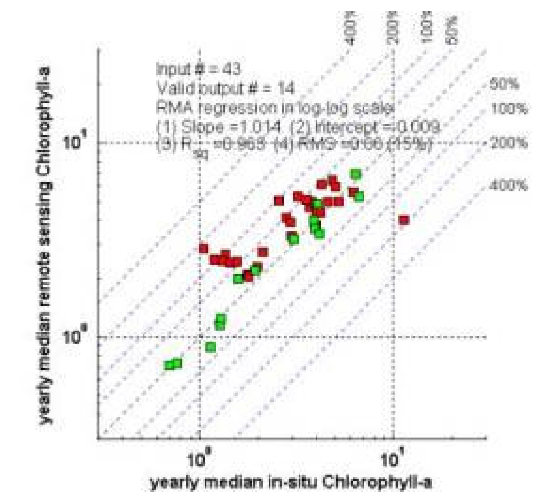

Figure 3.3. Comparison of geometric mean values ('median') of in situ measurements (x-axis) and remote sensing measurements (y-axis) in the year 2003. Points that are labelled red were excluded from the statistical analysis because less than 10 measurements (in situ or RS) were available in 2003.

3.2 The GEM Model

Various models have been developed simulating nutrient cycles and phytoplankton dynamics in the North Sea (Moll and Radach, 2003). Most of these models focus on the dynamics of the open North Sea and therefore have a relatively course model grid of 4 to 110 km. Detailed simulation of the dynamics of the Rhine river plume and phytoplankton dynamics in near-shore waters requires a finer model grid along the coast. A southern North Sea model especially dedicated to simulate the dynamics of the Rhine river plume has been developed at WL | Delft Hydraulics in 2003, for evaluation of effects of infrastructural changes in the coastal zone: the GEM (Generic Ecological Model) southern North Sea model (yet unpublished data). The model is an application of Delft3D modelling software (WL | Delft Hydraulics, 1999a; 1999b). The model builds further on earlier North Sea modelling efforts at WL | Delft Hydraulics and NICMM (e.g. Blauw *et al*., submitted; de Kok *et al*., 2001; Gerritsen *et al*., 2001; de Vries *et al*., 1998; van Pagee *et al*., 1988). It has been calibrated for an averaged year (representing 1995 – 1998) and for the period November 1988 – 1989.

As wind-driven variability of suspended solids concentrations are a major factor determining spring bloom timing a special effort has been dedicated to specify sufficiently accurate suspended solids concentration patterns. The resulting suspended solids forcing includes inter-annual variability due to different wind regimes.

The flow patterns in the GEM application for the southern North Sea are derived from a 3 dimensional hydrodynamic model simulation for the same grid (see Figure 3.4) with 10 sigma-layers. The flow simulation includes:

- Coriolis force;
- Advection-diffusion solver to compute e.g. density gradients;
- Pressure gradient terms in the momentum equation (density driven flows);
- Turbulence model to account for the vertical turbulent viscosity and diffusivity;
- Shear stresses exerted by the turbulent flow on the bottom;
- Wind stresses on the water surface;
- Drying and flooding of inter-tidal flats (moving boundaries) for both 2D and 3D cases.

An overview of the processes included in this application of the Generic Ecological Model is given in Figure 3.5. Process formulations are described by Blauw *et al*. (submitted). In summary nutrient cycles of nitrogen, phosphorus and silicate and phytoplankton dynamics are simulated in 3 steps: inorganic nutrients, nutrients in phytoplankton biomass and nutrients in dead organic matter. State variables for inorganic nutrients are nitrate (including nitrite), ammonia, ortho-phosphate and dissolved silicate. State variables for dead organic matter are: detritus carbon, detritus nitrogen, detritus phosphorus and detritus silicate and the same four variables in the sediment. State variables for phytoplankton are 4 species groups: diatoms, flagellates, dinoflagellates and *Phaeocystis*, which have each been subdivided in 3 physiological states: energy limited, nitrogen limited and phosphorus limited. Phytoplankton is subject to growth, respiration and mortality. Competition between phytoplankton species is simulated by the optimisation technique linear programming, which selects for the best adapted (combination of) species depending on environmental conditions. The application of linear programming for simulation of phytoplankton species composition is described in more detail by Los and Brinkman (1988). Besides the major processes in the nutrient cycle: uptake, mortality and remineralisation additional processes are included for nitrification, sedimentation and production, consumption and reaeration of oxygen. Attenuation coefficients for light in the water column are determined as the sum of extinction by phytoplankton, particulate organic matter, humic substances and background attenuation.

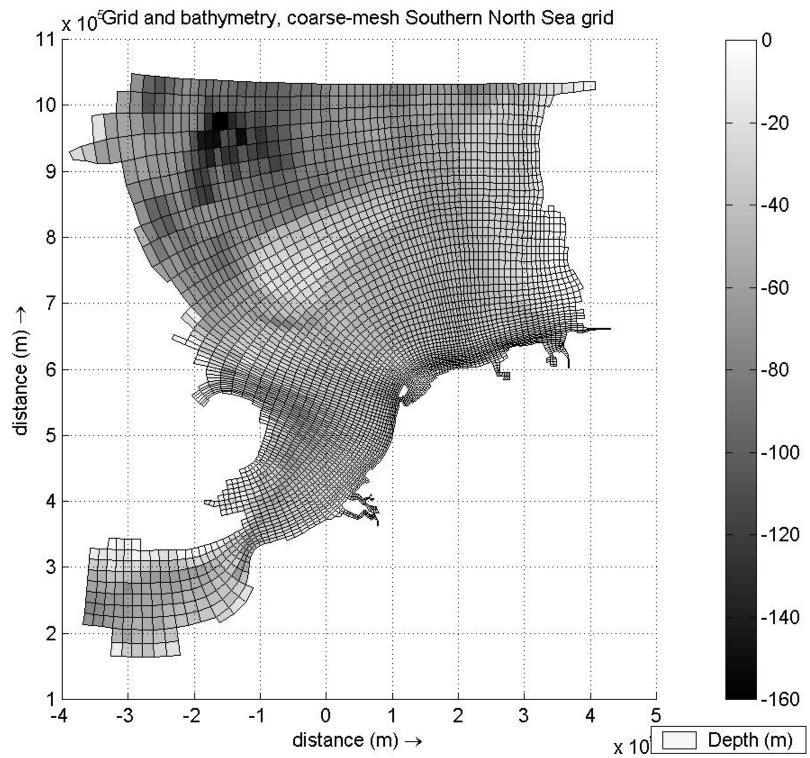

Figure 3.4 Model grid of the southern North Sea model.

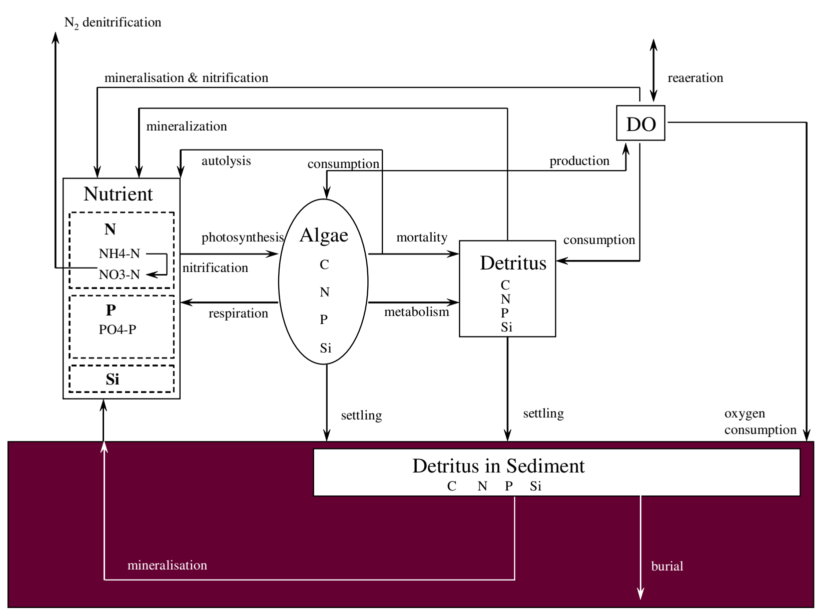

Figure 3.5 Overview of processes included in GEM.

The hydrodynamic model is run with a time step of 5 minutes. Spatially and temporally varying wind and pressure data from the meteorological model of the Royal Dutch

Meteorological Institute are used as model forcing. Forcing for air temperature, humidity and cloud cover are uniform over the area, using daily observations at station 'de Kooy' at the northwestern Dutch coast. Daily averaged discharge data are used for Dutch rivers and the Seine and yearly averages for other rivers. Water levels at the boundaries vary according to astronomic tides.

Transport of substances within the model and water temperature forcings are based on flow information from the hydrodynamic model. River inputs are based on daily observations of discharges and circa 2-weekly observations of concentrations near the river mouths made by the Dutch Ministry of Transport and Public Works (www.waterbase.nl). Concentrations at the model boundaries (Channel and Atlantic Ocean) are based on studies by Laane (1992) and Laane *et al*. (1993).

Suspended matter concentrations have a large impact on phytoplankton dynamics in Dutch coastal waters. To enable reliable simulation of phytoplankton dynamics in Dutch coastal waters recently a new method has been developed for approximation of spatial and temporal variability of suspended matter concentrations. This method combines information on spatial and seasonal variability derived from remote sensing with information on short term temporal variability due to wind effects.

The effect of wind speed on short-term variability of suspended matter concentrations has been studied within the HABES-project (Harmful Algal Blooms Expert System) (Blauw *et al*., 2004). Time series of wind speed observed by the Royal Dutch Meteorological Institute and turbidity observed by the Smartbuoy (Mills, 2002) at station Noordwijk 10 have been analysed. A significant correlation between turbidity and averaged wind speed during the preceding week was found. As buoy data were only available for station Noordwijk 10 km, information about variability of suspended matter concentrations at other locations has been derived from monitoring data from 2001 to 2003 at 39 locations in Dutch coastal waters (www.waterbase.nl). In these data there was a clear correlation between the averaged suspended matter concentration (C) per monitoring station and its standard deviation (S):

$$S = -0.0031 * C^2 + 0.8682 * C - 0.7029 = (\mathrm{R}^2\ 0.95) \tag{3.1}$$

Assuming that most of the temporal variability is due to wind-induced resuspension this information can be used in combination with remote sensing data to construct a forcing function for suspended matter concentrations. This has been done as part of the ISCHA project. The forcing function is constructed as follows:

1. Monthly composites of remote sensing data on total suspended matter concentrations observed by the MERIS satellite have been constructed by IVM;
2. These monthly composites have been translated to the model grid and interpolated to create a spatial and seasonal pattern of suspended solids concentrations (C_{ss});
3. For every model segment and every day a standard deviation has been calculated using equation 1. The suspended solids concentration C_{ss} has been used as averaged suspended matter concentration in the equation;
4. The daily averaged wind speed (W_d), as observed by the Royal Dutch Meteorological Institute near Den Helder is rescaled with the long term averaged wind speed (W_a = 5.5) according to:

$$W_r = W_d - W_a \tag{3.2}$$

5. A wind induced temporal variability is superimposed on the spatial and seasonal suspended matter pattern derived from remote sensing data (C_{ss}) by multiplication with the corresponding standard deviation (S), the rescaled wind speed (W_r) and a calibration factor (a = 1.5) according to:

$$C_{tv} = C_{ss} * S * W_r * a \tag{3.3}$$

3.3 Field data

The Dutch Ministry of Transport and Public Works has maintained a continuous monitoring programme since the 1970's measuring many chemical and biological parameters on a large number of sampling locations in both fresh water and marine waters. Sample at the North Sea are taken along a set of transects, at several distances off the coast (e.g. 2, 5, 10, 20, 50, 70, 100 km) on approximately a monthly schedule. Measured parameters include a.o. suspended matter, chlorophyll-a and phytoplankton species composition. Species composition is relevant as some harmful algal events, like those involving toxicity, are related to specific algal species. After about a year these data become available to the public (see http://www.waterbase.nl).

4. User information requirements

This report gives an overview of the information flow required for the proposed harmful algal blooms early warning system. In the present workplan the early warning system will be operated with input of RIKZ field data, remote sensing information from IVM and model information from WL | Delft Hydraulics. Schematically the information flow can be represented as shown in Figure 4.1.

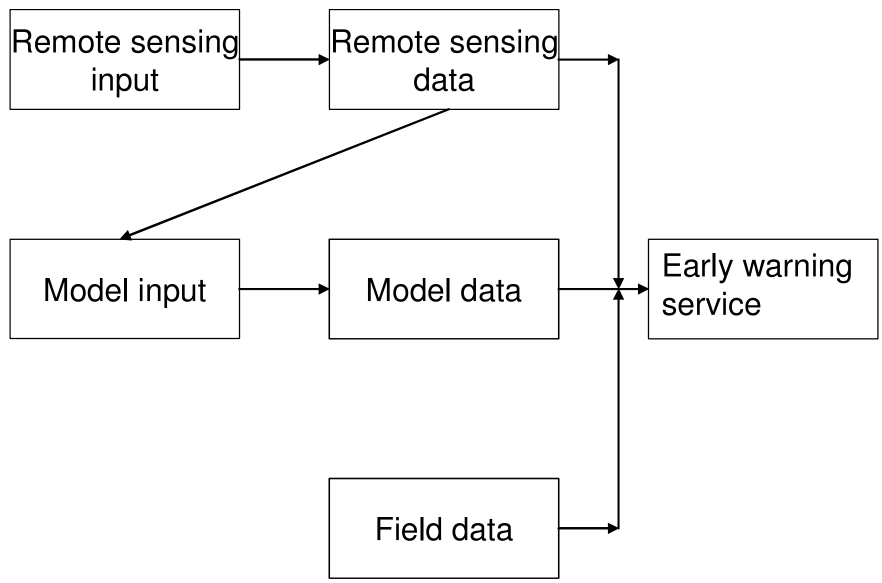

Figure 4.1 Schematic representation of information flow in the proposed early warning service.

The different components of the information flow shown in Figure 1 are discussed in more detail below.

4.1 Early warning service

The aim of the early warning service is to warn the Zeeland division of ‘Rijkswaterstaat’ and shellfish farmers in the Oosterschelde in case there is a high risk of harmful algal blooms. Mitigating measures can then be taken to prevent mass mussel mortality and problems due to oxygen deficiency in semi-enclosed tidal inlets such as the Grevelingen and ‘Veerse Meer’. A high probability of harmful algal blooms due to high biomass (often due to *Phaeocystis* blooms) occurs mainly in the period April – May every year. Therefore, the early warning service only needs to be operational in this 8-week period. During this period a reporting frequency of twice per week is proposed: at Monday afternoon and Thursday afternoon, so the bloom predictions can be based on up-to-date data. This allows for processing of information (from remote sensing, models and field data) on Mondays and Thursdays and releasing a HAB bulletin on Tuesday and Friday. The criterion for harmful algal bloom alarm has historically been when the *Phaeocystis* concentration in field data collected near the Brouwersdam exceeded 5 million cells/L. This corresponds with a CHLa concentration of circa 2.5 µg/L. This criterion may be reconsidered during the development of the early warning system, based on the availability of additional (spatial) information from remote sensing and models. The analysis and reporting of the potential risk of harmful algal blooms in the Oosterschelde will be based on available data from remote sensing, models and field observations.

4.2 Field data

RIKZ collected samples for *Phaeocystis* cell counts up to 5 times a week, during the period April-May 2003. Every Friday the results became available. Occasionally also samples from the stations Goeree 6 km, Walcheren 2 km and the Oosterschelde are available from the BIOMON programme and the TOXALG*KUST programme. Data on chlorophyll-a concentrations usually become available with a delay of several weeks to months.

4.3 Remote sensing data

For every reporting period of the early warning service, remote sensing images for chlorophyll-a will be sent by IVM to RIKZ: one for every day that suitable images are available during the reporting period. The remote sensing data will preferably be delivered by e-mail, if the file size of the images allows that. To give a good overview of phytoplankton abundance in Dutch coastal waters it is proposed that the remote sensing data cover the area from the Belgian border to the Marsdiep, till 100 km from the coast. The images will be accompanied by information on the (un-) certainty on the estimated chlorophyll-a concentrations and the concentrations of suspended matter to parameterize the GEM model.

The file contains a header and data with the following contents: project (ISCHA), producer (IVM, RP), sensor (MERIS RR), date observation, date processing, algorithm version, coordinate convention.

Per pixel information is given in ASCII (lat, long, True/False in case the PC13 flag is raised or in case of clouds or land pixels, CHL mg m^{-3}, error CHL mg m^{-3}, TSM g m^{-3}).

4.4 Model data

Three types of model predictions can be made that may provide useful information for the early warning service:

1. Model predictions of chlorophyll-a concentrations and *Phaeocystis* abundance based on environmental data (weather forecast), without taking into account the information from remote sensing. The advantage of these types of predictions is that they are always available, also when remote sensing information is absent due to too much cloud cover. The disadvantage is that additional information from remote sensing is not taken into account;
2. Model predictions of chlorophyll-a concentrations based on transport of chlorophyll-a patterns observed by remote sensing;
3. Model predictions based on transport and growth and mortality of chlorophyll-a patterns observed by remote sensing. For this approach the information on chlorophyll-a concentrations needs to be translated to concentrations of different phytoplankton

groups. The assumptions to be made for this are a source of uncertainty in the model. Possibly the phytoplankton concentrations are consistent with the values of other model variables, such as salinity, suspended matter and nutrient concentrations. Whether this approach is feasible and yields better results than the model prediction based on just transport of observed chlorophyll-a is one of the questions to be studied within this project.

It is proposed that the first type of model predictions will be delivered to the early warning service for every reporting period. The second (or third) type of model prediction can only be made in case remote sensing information of sufficient quality and spatial coverage is available. Prediction of bloom transport is only useful if enhanced concentrations of chlorophyll-a are observed in coastal waters near the Oosterschelde. During this study criteria will need to be specified on the required quality and spatial coverage of the remote sensing information and on which levels of chlorophyll-a would be considered a potential risk. It is proposed that model predictions on the transport (an possibly growth and mortality) of chlorophyll-a patterns observed by remote sensing will only be made when the criteria discussed above are met. In that case IVM will send the remote sensing data to WL | Delft Hydraulics.

The model data will be delivered preferably by e-mail for every half-week period. The model results will be presented as a series of maps covering the Voordelta. The precise area and time interval between the maps will be determined during this study, optimizing on information content and file size. The model results may also be provided as an animation of the day-to-day model results.

4.5 External input conditions

Remote sensing input

The MERIS images needed for the processing of chlorophyll-a maps are delivered directly or indirectly by ESA to IVM. In the hindcast mode we have obtained the data as part of the REVAMP dataset. For a try out of the near-real time delivery the 2005 data were obtained from ACRI (France). More details about the acquisition of remote sensing input will be described in the technical implementation plan (Chapter 5).

Model input

The model consists of two modules: FLOW and GEM. The FLOW module simulates water transport and other physical variables, such as currents (speed and direction), water levels, turbulence and water temperature. The GEM module simulates the transport and processes affecting substances in water, such as growth and mortality of phytoplankton, uptake of nutrients by phytoplankton, release of nutrients upon decay of organic matter and oxygen concentrations. Table 1 gives an overview of the input data required for both modules and the suggested data source. Both modules require information on:

- Initial conditions: values of all model variables in all model segments at the start of the simulation;
- Forcing: environmental data that affect the model simulation, but that are not simulated within the model;
- Rivers: discharges and concentrations of substances in rivers;

- Boundary conditions: values of model parameters on the edges of the model grid i.e. the English Channel and the Atlantic Ocean.

In case the transport of chlorophyll-a patterns as observed by remote sensing is simulated, the observed concentrations will be used as initial condition for chlorophyll-a in the model.

Table 4.2 Overview of required model input and the proposed data source for the model simulations of the early warning service.

Data type	Module	Parameters	Data source
Initial conditions	FLOW	all model variables	simulation of preceding period
	GEM	all model variables	simulation of preceding period
Forcings	FLOW	Wind	HIRLAM, KNMI model forecast
		pressure	HIRLAM, KNMI model forecast
		air temperature	HIRLAM, KNMI model forecast *
		humidity (%)	HIRLAM, KNMI model forecast *
		Cloud coverage	HIRLAM, KNMI model forecast *
	GEM	Solar irradiance	HIRLAM, KNMI model forecast *
		water temperature	simulated by FLOW module
		Wind	HIRLAM, KNMI model forecast
		suspended matter	2-monthly composites of MERIS TSM images, with variability superimposed
Rivers	FLOW & GEM	discharge	knowledge rules and realtime observations at Lobith *
		salinity	salinity is assumed zero
		temperature	air temperature
	GEM	all model variables	knowledge rules and realtime observations at Lobith *
Boundary conditions	FLOW	salinity	Flyland model
		temperature	Flyland model
	GEM	all model variables	Flyland model

The data sources marked with * are the proposed data sources once the service is operational. However during the development and testing of the service it is proposed to first use the (more reliable) observed data on a.o. discharges and concentrations at the river mouths instead of Lobith.

4.6 A HAB bulletin

Next to the information content that is required by the various partners, it turns out during this project that the way the information is transferred to RIKZ is equally important. All three partners have substantial knowledge of the area and the quality of the information that should be communicated together with basic data. We have chosen to follow the approach taken by NOAA (Stumpf *et al*., 2003). Beginning in 1999, the National Oceanic and Atmospheric Administration has issued the Gulf of Mexico **HAB Bulletins** to support state monitoring and management efforts. These bulletins involve analysis of satellite imagery with field and meteorological station data. The effort involves several components or models: (a) monitoring the movement of an algal bloom that has previously been identified as a HAB (type 1 forecast); (b) detecting new blooms as HAB or non-HAB (type 2); (c) predicting the movement of an identified HAB (type 3); (d) predicting conditions favourable for a HAB to occur where blooms have not yet been observed (type 4). A prototype can be found in Appendix 1. It contains a simple description of the actual situation (RS image and supporting in-situ measurements) and a model prediction a few (normally five) days ahead.

4.7 Decision rules for an ISCHA service

Finally the simple decision support rules on the handling of the ISCHA information is defined by RIKZ Middelburg as follows:

1. Start: week 13 (1 april);
2. Phytoplankton model simulations, field observations and processing of MERIS images on Mondays and Thursdays (see also section 4.1);
3. Is CHL at Brouwersdam or Oosterschelde mouth >10 µg/l in field data, MERIS images or model predictions?

   If yes: perform transport model simulations (if suitable MERIS information is available) and give warning (bulletin on Tuesday/ Friday);

   If no: go to point 2 (or withdraw the previous warning).
4. Stop in week 21 (end of May).

5. Development of a pre-operational product

5.1 Basic flow-diagram

WL | Delft Hydraulics has set up an automated procedure to make predictions about the fate of phytoplankton blooms observed with remote sensing. With this automated procedure predictions have been made for the fate of observed phytoplankton blooms in spring 2003 in the Voordelta.

The modelling work undertaken in this project and which, together with the processing of the remote sensing data by the Instituut Voor Milieuvraagstukken (IVM), forms the basis of the future ISCHA service has been schematised in Figure 5.1 .

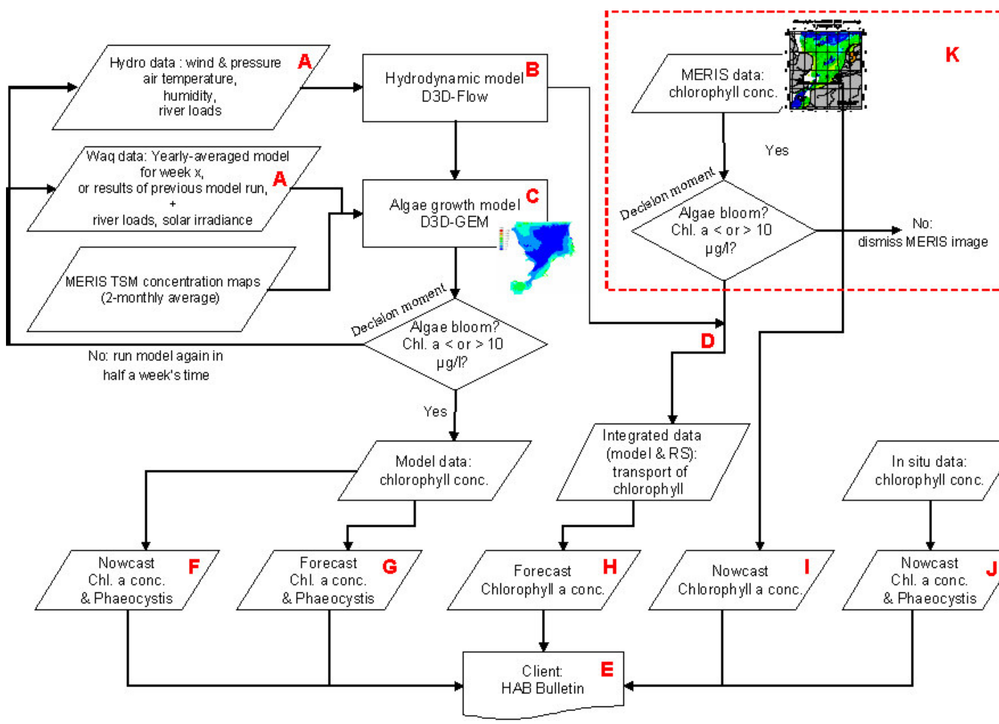

Figure 5.1 Scheme of the modelling data flow and procedures used within ISCHA.

This figure illustrates the steps that are taken to create a HAB bulletin. In short there are three chains of data and work flow which together create a HAB forecast which is incorporated into the HAB bulletin;

1. The 'model chain', in which the hydrodynamic and algae growth model together provide model output data on chlorophyll concentration. This follows a 'Yes' decision at the decision moment: is the chlorophyll *a* concentration < or > 10 µg / l?. The model output data on chlorophyll concentration can be transformed into:
   - A nowcast (i.e. the current situation) of chlorophyll *a* and Phaeocystis concentration in the Voordelta ('F' in Figure 5.2);
   - A forecast of the chlorophyll *a* and Phaeocystis concentration during a certain time period, e.g. a few days ahead ('G').

2. The 'remote sensing chain', in which MERIS images are processed daily up to chlorophyll *a* concentration. This is carried out by IVM (see Chapter 5.2). If the chlorophyll *a* concentration is > 10 µg / l in the MERIS image, two products can be derived:
   - The chlorophyll *a* concentration from the MERIS image is integrated with the hydrodynamic model to calculate the transport of chlorophyll. This results in a forecast of the chlorophyll *a* concentration ('H);
   - A nowcast of the chlorophyll *a* concentration is derived directly from the MERIS image ('I').
3. Although not necessarily a chain of processing, a third source of data is the field data (or in situ data), which can provide information on the current situation of chlorophyll *a* and Phaeocystis concentration ('J').

The workflow under 1, and partly 2, is primarily the work carried out by WL.

5.2 Near Real Time processing of MERIS information

An overview of the activities will be given below, based on the different activities that can be distinguished within the remote sensing chlorophyll map production. Figure 5.2 gives a schematic overview of these activities; a more detailed workflow of the 'remote sensing' chain in figure 5.1. The different activities are labelled in capitals A through D and are discussed in the next sections.

Data acquisition (A)

The chlorophyll map production from remote sensing data within the ISCHA service depends on MERIS data. MERIS level 2 data can be obtained from 4 sources:

1. From ACRI (through the MARCOAST project) in near real-time. In practise the data are transferred from ESA to ACRI within 12 hours. The data are processed to level2 (IVM only uses the MERIS RRS) within 8 hours and made available to IVM;
2. Also from ACRI in a batch per year afterwards at the end of the year;
3. From ESA as a backorder;
4. Directly from the MERIS satellite by setting up a ground receiving station.

As the ISCHA service depends on near real-time data, option 2 and 3 are not feasible, while option 4 is uneconomical, considering the expected remaining lifespan of MERIS. Option 1, obtaining images trough the MARCOST project, therefore remains as the preferred data acquisition method.

Processing, including hardware and software (B)

The processing can be expressed in terms of working hours for a remote sensing specialist. Processing costs may be reduced by automation but this will require additional initial investment. The MERIS processing can be performed on a standard PC using MATLAB.

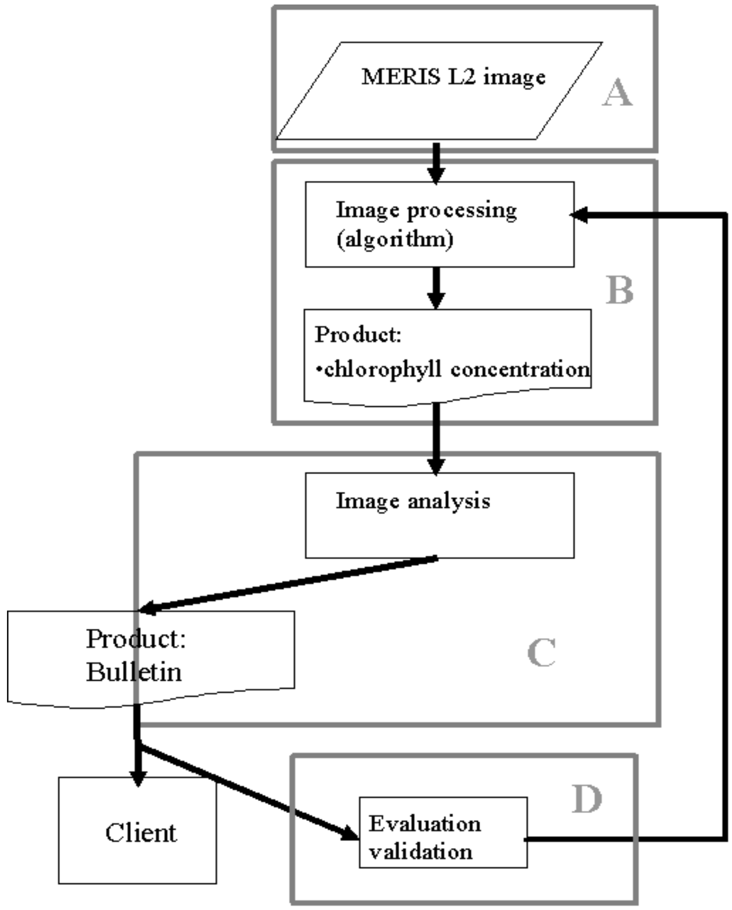

Figure 5.2 Schematic overview of the remote sensing derived chlorophyll map production at IVM (activities marked A-D).

Analysis and bulletin composition (C)

As with the processing, the analysis and bulletin composition costs are expressed in terms of work including a remote sensing specialist. The analysis also includes the model data provided by the WL. The bulletin has a strictly fixed format and is divulged by email. It is assumed that there will be two bulletins distributed per week.

Evaluation and validation (D)

It is necessary to evaluate the performance of the ISCHA service each year, in order to improve and fine-tune the image processing.

6. Results for the April 2003 Voordelta case

In this chapter the results of in-situ measurements, remote sensing analysis and the outcome of model for the year 2003 are presented. The results are discussed with reference to the requirements that have been defined in the previous chapters. In short, is the ISCHA information service reliable and sufficient to issue a HAB warning?

6.1 Preamble to the inter-comparison of information

The comparison of in situ data and remote sensing data (also called 'validation') is a delicate subject because of the different nature of the measurements. First of all, the spatial scale of the measurements differ orders of magnitude. While in-situ measurements typically sample about 10 litres of waters, a remote sensing measurement covers one square kilometre, averaged over a certain surface layer (depending on the concentration: only a few to over fifty meters). The model has a curved grid and gives an average value for this grid cell. Secondly, in-situ measurements typically extract the algal pigments from the cell, where remote sensing 'sees' the algal pigments as they interact with the underwater light field in the intact algal cells. Thirdly, because of the rapidly changing conditions on the North Sea, remote sensing and in-situ measurements are only directly comparable when sampled within a small time window (~1 hour), unfortunately this is only rarely the case. The match-up of in-situ and model results is less problematic, since model results are available at a much higher temporal resolution. Finally, the measurement protocols that are used by national monitoring agencies can differ in a number of aspects, ranging from sampling methods to extraction solvent. These differences can have a significant effect on the measured chlorophyll-a concentration (as pointed out by several intercomparison experiments, see www.quasimeme.org).

6.2 Chlorophyll-a as a proxy for *Phaeocystis globosa*

Remote sensing cannot (yet) discriminate between the occurrence of *Phaeocystis globosa* and other algae species. Instead it measures the level of Chlorophyll-a. Therefore one of the key elements of the service is the relation between *Phaeocystis globosa* cell counts and *in situ* HPLC-measured chlorophyll-*a* concentration in the Voordelta.

In Figure 6.1 the data from January-June 2003 from monitoring stations Walcheren 2, Walcheren 20 en Goeree6 have been collected (All data are from the Rijkswaterstaat routine (MWTL) monitoring programme). The lines are calculated chlorophyll-*a* values based on a carbon content of 1.2 pmol per *Phaeocystis* non-flagellated cell (Rousseau *et al*., 1990) and a carbon to chlorophyll-*a* ratio of 50 (continuous line) and 10 (dashed line).

If the *Phaeocystis*-bloom is defined as a cell concentration exceeding 10 million per litre, the chlorophyll-*a* concentration is roughly >10 µg per litre. From this analysis we propose that levels of Chlorophyll-a can be employed in the Voordelta in the following way:

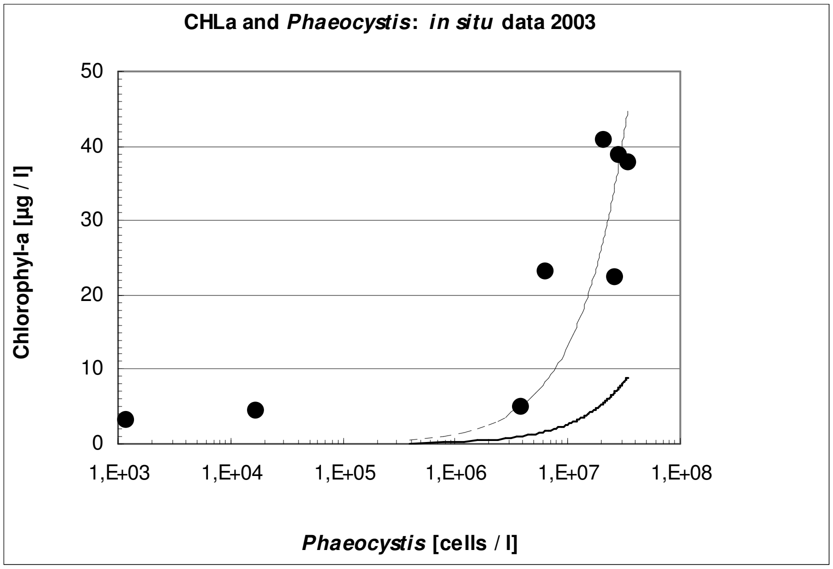

Figure 6.1 Relation between Phaeocystis globosa *cell counts and* in situ *HPLC-measured chlorophyll-*a *concentration in the Voordelta.*

1. Chlorophyll-*a* concentration is roughly <10 µg per litre. Green. The concentration is conforming to the background levels and no *P. globosa* is likely to be present;
2. Chlorophyll-*a* concentration is between 10 and 20 µg per litre. Orange The concentration is exceeding background levels and if *P. globosa* is present a HAB event is likely to be present;
3. Chlorophyll-*a* concentration is roughly >20 µg per litre. Red . The concentration is at bloom level. A rapid check on algal species (and toxicity) is required.

6.3 HAB detection by remote sensing

The full set of MERIS images of the North Sea has been analyzed. The number of images available is on average one per day.

- March: 38 observations;
- April: 24 observations;
- May: 41 observations.

However, these images do contain many clouded scenes and the Voordelta in particular is only six days fully observed in the bloom period. More information is available scattered over the area, depending on weather conditions.

The most important images are shown in Figure 6.2. The maps cover a much larger area. In this project an animation is produced (see website IVM) of all data that more clearly demonstrates that the spring bloom in the Dutch coastal zone is a widely occurring phenomenon.

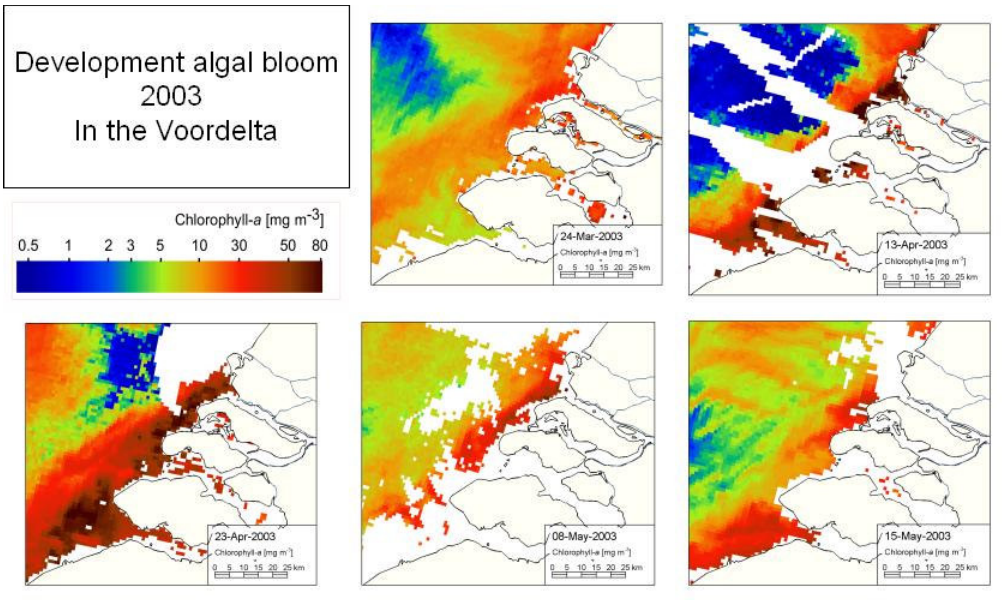

Figure 6.2 Development of an algal bloom in 2003. The best images for this region have been selected from the MERIS REVAMP archive. White indicates land, clouds or bad data.

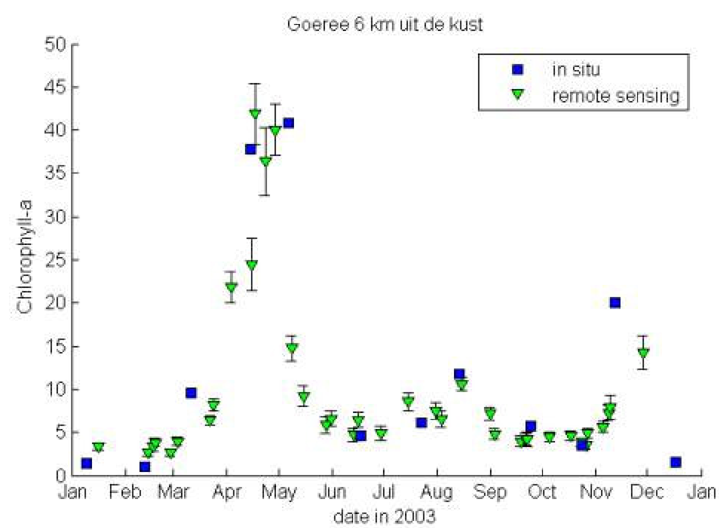

Figure 6.3 Time series of chlorophyll-a concentration (mg m^{-3}) in 2003 for in situ (blue squares) and remote sensing data (green triangles).

In Figure 6.3 the time series for the turbid Dutch coast station ('GOEREE6') is presented. This station covers different regimes with low- and high-suspended matter and dissolved organic matter, and also cover more than a decade in chlorophyll-a concentrationThe vertical error bars on the remote sensing data points indicate the standard error. The error in the in-situ measurements is unknown. Although it is difficult to interpret these kind of images (because the samples were taken at different days), the timing (April) and magnitude of algal blooms seen in remote sensing and in-situ data series are in good agreement. Also the error bars on the remote sensing data seem to provide a good estimate of the true error in these measurements.

The analysis of the MERIS data should give answer to a number of important questions:

1. Are there sufficient observations in the bloom season?

Yes and no, In 2003 elevated levels (above 10 µg per litre) were confirmed at April 13 and April 15 when the concentrations at some stations were already above the red limit (> 20 µg per litre). The transition from safe (confirmed at March 24) to potential risky has not been covered. At Goeree 6 a total of 6 reliable remote sensing measurements of the full bloom, were compared to 2 MWTL data points. The decline of the bloom at the end of April was well covered, going at Goeree 6 from 25 to 19 µg per litre in 6 days.

2. Can the observation be delivered in time?

Yes. The processing itself and delivery of the maps can be done within 24 hours. This was tested and proved for a test service in spring 2005, based on a contract with ACRI. Thus the processing on Mondays or Thursday can cover information of the last three to four days.

3. Is the accuracy enough to detect elevated levels in time?

Yes. The information in Figure 6.3 confirms that the measurements are accurate enough to establish the three classes green, orange and red. From the 2003 data at Goeree 6 the typical uncertainty derived fro the retrieval results is as follows:

- Mean Green 5 µg per litre has a typical error of 1.2 µg per litre;
- Mean Orange 15 µg per litre has a typical error of 3.5 µg per litre;
- Mean Red 40 µg per litre has a typical error of 7.2 µg per litre.

From the 2003 hind cast exercise it is concluded that the remote sensing information has been severely restricted by clouds. Based on the MERIS data alone the early warning for elevated levels would have been issued on Monday April 14., the first processing day after a clear observation of the area on April 13. After this a total of 6 very relevant images are produced to describe the evolution in space and time of the bloom and providing a independent source for testing the model nowcasting and model forecasting.

6.4 Model output and prediction

Two types of model simulations have been performed: phytoplankton simulations and transport simulations (option 1 and option 2 respectively as described in section 4.4)

Figure 6.4 shows time series of chlorophyll-a (left panel) and *Phaeocystis* (right panel) in the phytoplankton model, in comparison with field data and remote sensing data, at 3 stations in the Voordelta area. The start of the bloom coincides with a sharp drop of suspended solids concentrations, due to a period of low wind speeds (see Figure 6.5). The forcing function for suspended matter concentrations, based on seasonal and spatial patterns from remote sensing and short-term variability due to wind speeds, reproduces field observations of suspended matter concentrations very well.

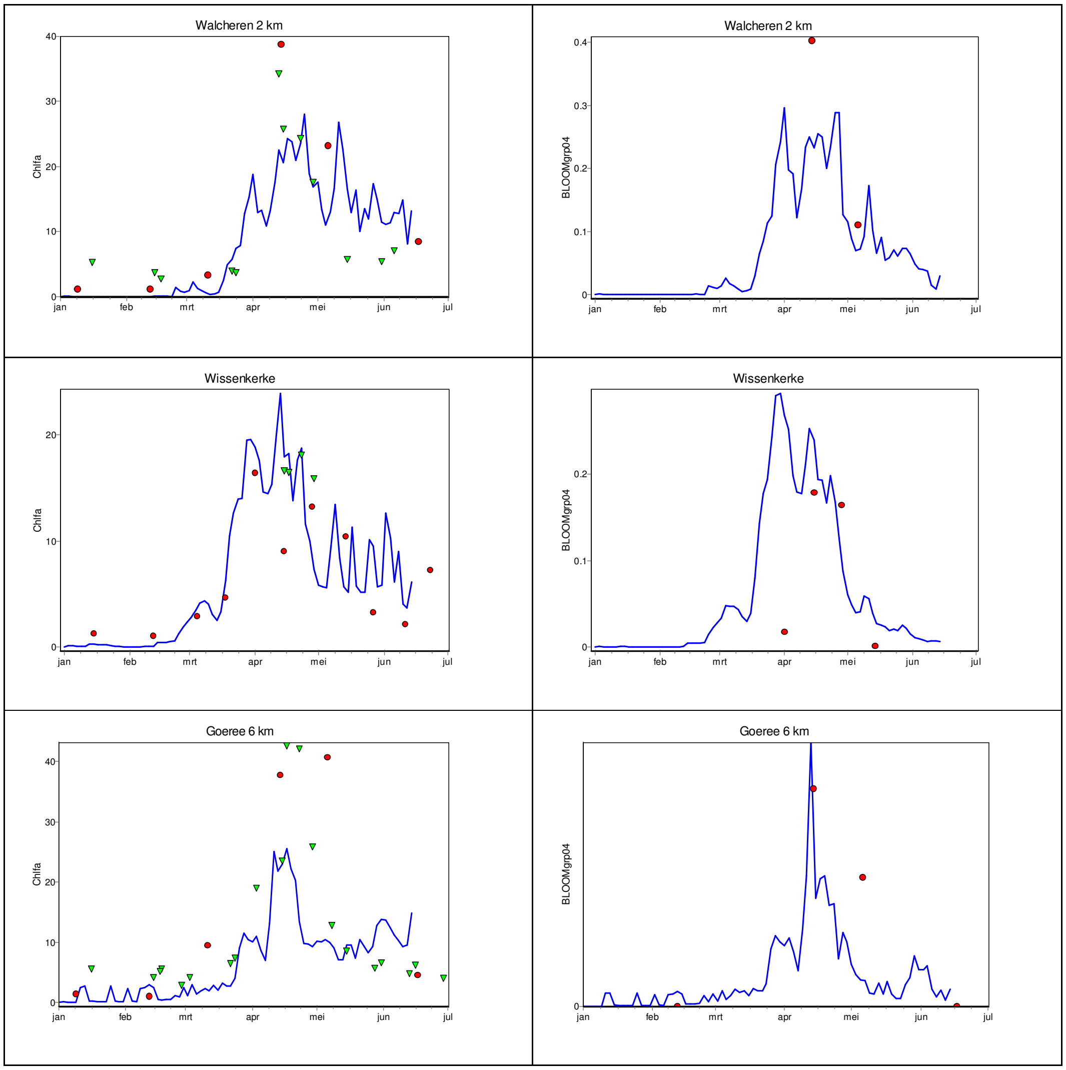

Figure 6.4 Time series of chlorophyll-a (left) and Phaeocystis *(right) at 3 stations in the Voordelta and Oosterschelde, for 3 data sources: GEM model (blue line), field data (red circles) and remote sensing data (green triangles).*

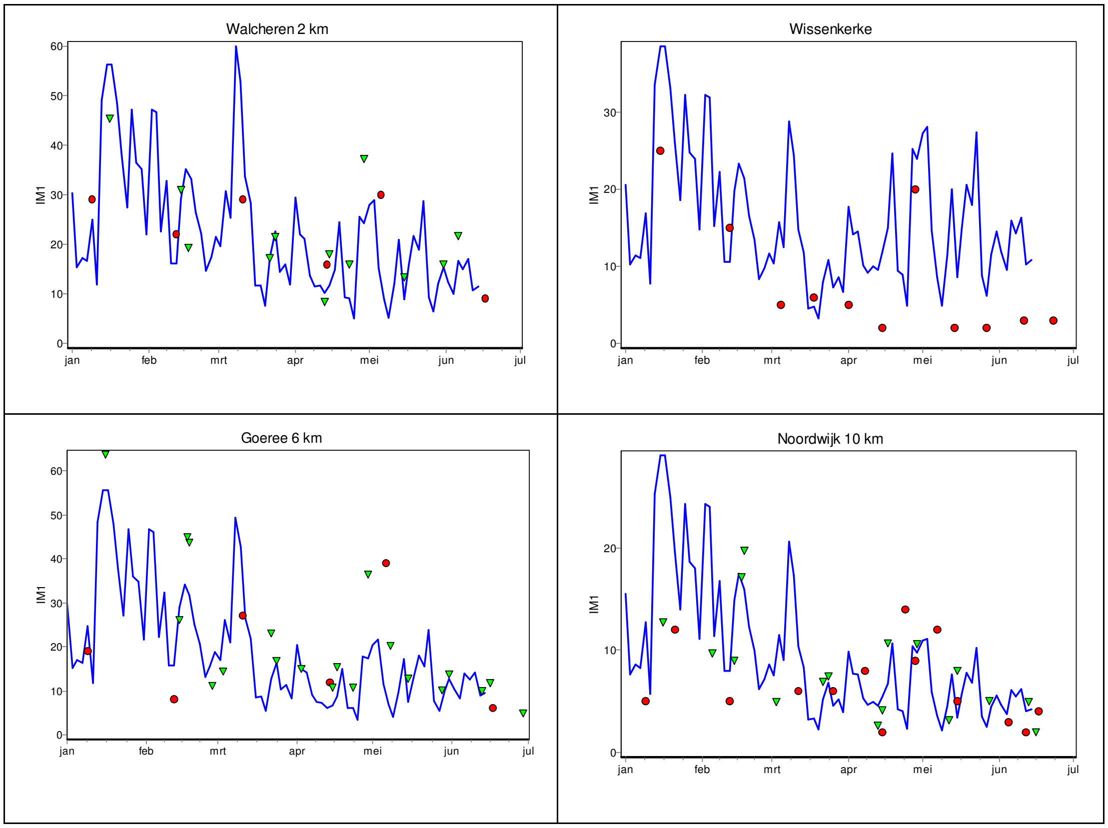

Figure 6.5 Simulated suspended matter concentrations in comparison with field observations and remote sensing data at 4 stations in Dutch coastal waters.

More information on the spatial evolution of the algal biomass (expressed as chlorophyll-a concentrations) is provided in Fig. 6.6 where the outcome of the GEM phytoplankton model in the Voordelta is depicted on 8 days in March and April 2003. It shows that the phytoplankton bloom develops first *within* the Oosterschelde estuary already in mid March. The measurements in Wissenkerke begin April make it clear that Diatoms dominated this bloom. This early bloom can be related to the combination of smaller depth and lower turbidity, compared to the near coastal zone. The peak of the bloom in the Voordelta area is during the first 2 weeks of April. Note that all model results show a decline in biomass in the first week of April, a result that is reproduced in the Brouwersdam data (see below). All evidence suggests that the period between 10 and 20 of April is the maximum of the bloom in the near coastal zone outside the Brouwersdam. At 23 April the bloom is already declining. If the harmful algal bloom warning would be based on the model, it would be issued on March 26th.

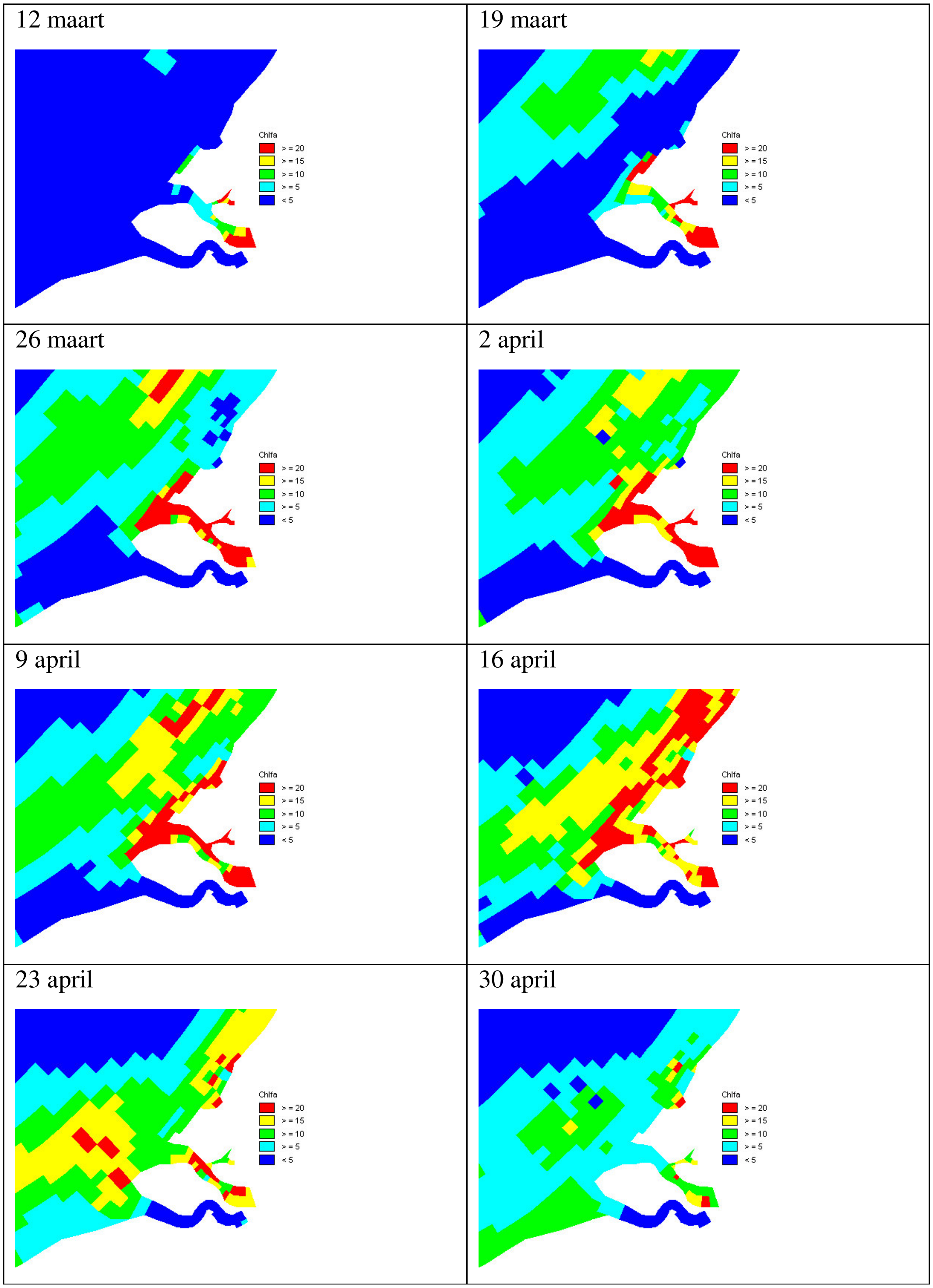

Figure 6.6 Bloom development and decay, expressed as chlorophyll-a levels simulated by the phytoplankton model.

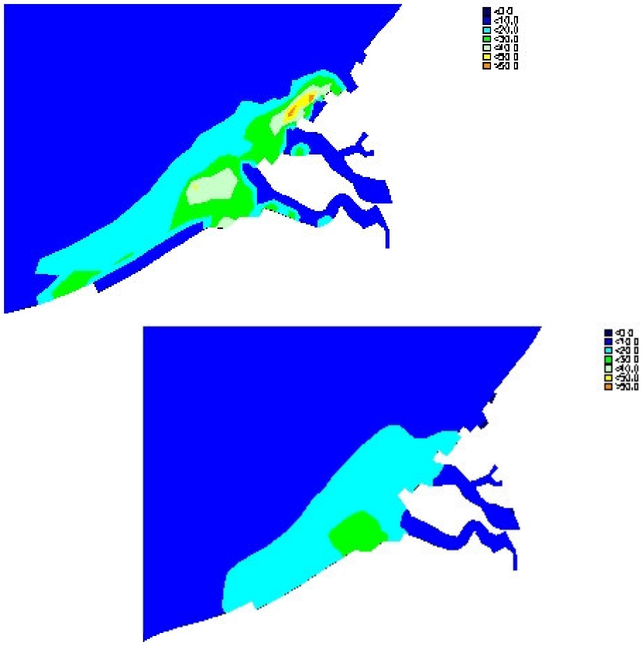

Figure 6.7 Chlorophyll-a distribution at 23 April according to MERIS data (left) and the chlorophyll-a distribution one week later according to the transport model (right).

The transport model has been run for 4 relatively cloudless days in April. The transport model is specifically useful for prediction of blooms that are transported into the Oosterschelde from the Voordelta area. Figure 6.7 shows the remote sensing data of April 23, projected on the model grid and the predicted distribution of this bloom one week later. According to this simulation the bloom would not be transported into the Oosterschelde in 2003.

6.5 Observation of blooms with field data

There is a lack of in-situ measure at sea and near the coast in 2003 to fully cover the spring bloom. Therefore, the few points of Rijkswaterstaat taken at the stations Goeree 6, Wissenkerke (in the Oosterschelde) and Walcheren 2 were used for the inter-comparison with remote sensing and model results (previous sections). However, there is information on the occurrence of *Phaeocystis globosa* near the *Brouwersdam,* the entrance to Lake Grevelingen (Figure 6.8).

The measurements, taken with a flowcytometer started at the last day of March. After April 11 the bloom critical level (assuming a reference level of 10 million cells/L *Phaeocystis)* was exceeded. Apparently no measurements were taken in the weekend of 12, 13 April, such that the first positive detection of a HAB was at April 14, the same day that a remote sensing HAB detection confirmed the bloom in the whole coastal area. The returned to sub-critical levels at the Brouwersdam begin of May 2003.

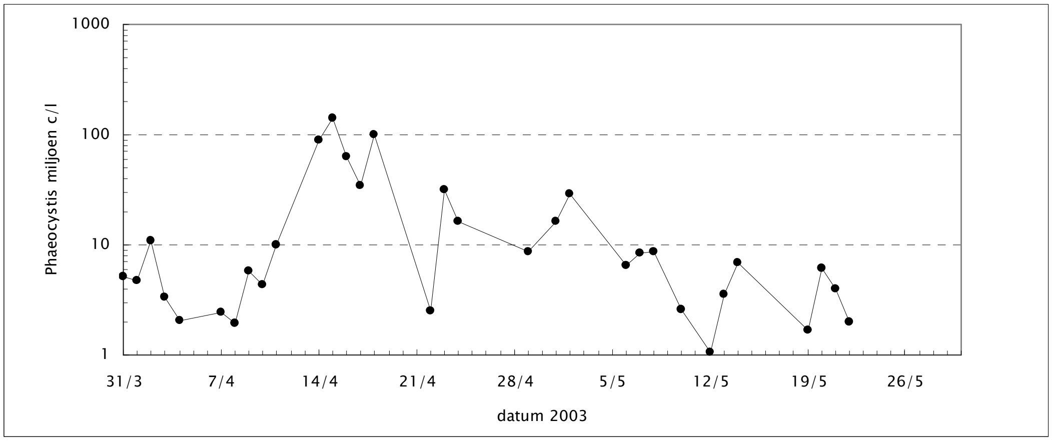

Figure 6.8 Temporal evolutions of the Phaeocystis globosa cells at the Brouwersdam.

Figure 6.9 shows the field data on *Phaeocystis* concentrations at 5 stations in the Voordelta area. Chlorophyll-a concentrations above the 10 µg/l threshold are first observed in the Oosterschelde area at April 1st. *Phaeocystis* concentrations above the 10 million cells/L threshold are first observed in the Oosterschelde at April 15th.

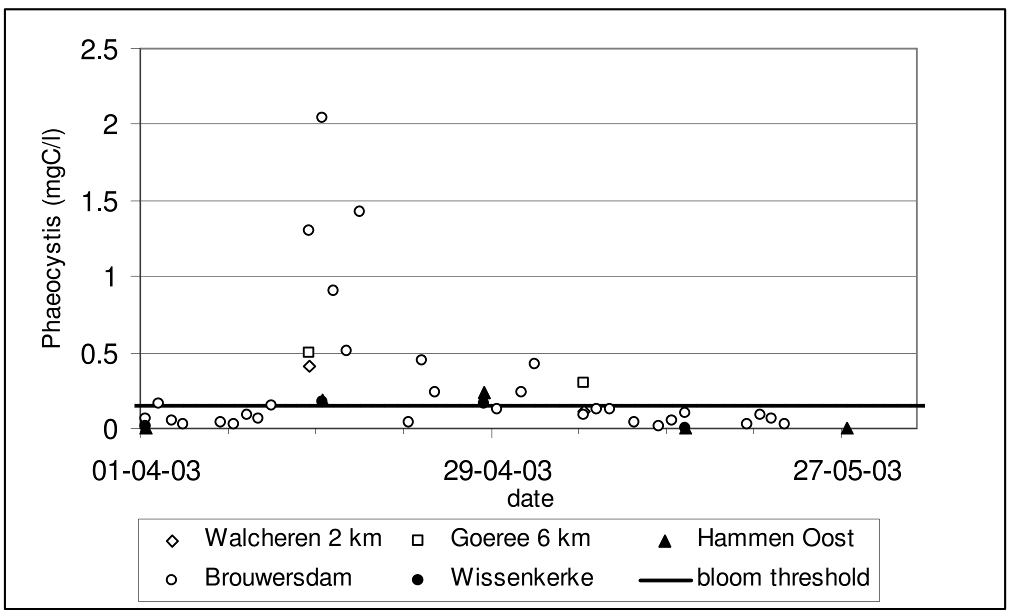

Figure 6.9 Field observations of Phaeocystis *in spring 2003 at 5 locations in the Voordelta area.*

6.6 Bloom development and early warning

Finally all data sources have been combined and analyzed with the goal to identify an optimized system that would have given an early warning for the development of a harmful Phaeocystis bloom. The study started with the assumption that HAB develop in the Voordelta and might flush in the Oosterschelde. This has been demonstrated for the harmful algal bloom in 2001 (Hesselmans *et al.*, 2005). In the ISCHA study we have learned that in 2003 this has not been the case. Instead elevated levels first developed within the Oosterschelde. Outside the Oosterschelde a bloom developed very close to the coast (within 6 km) between 10 and 20 April. This elevated bloom slowly decayed and was transported southwards past the mouth of the Scheldt river (Figure 6.6).

This implies that a HAB early warning system should be able to handle two scenarios:

- Imported bloom scenario: HAB development within 6 km from the coast, that is transported into the Oosterschelde with wind-driven currents (e.g. 2001);
- Local bloom scenario: bloom development within Oosterschelde and the need to discriminate fast between Diatoms and Phaeocystis (e.g. 2003).

Remote sensing data on chlorophyll-a within the Oosterschelde estuary are sparse, since the vicinity of land complicates the interpretation of the images. Therefore remote sensing data have limited added value in case of a local bloom scenario. In case of a bloom in the Voordelta, remote sensing can provide useful information on location and distribution of the bloom. In combination with a transport model this results in more reliable predictions about the probability of imported blooms than if only the phytoplankton model would be used. Unfortunately cloud cover during the peak of the blooms in the Voordelta area restricted the use of this approach in 2003.

Model data and field data are equally useful for local blooms and for imported blooms. With the present field monitoring effort, the model is the only data source that can give information on the formation of local blooms. In general models are the only data source that can provide information about the future, both for local and imported blooms.

The MWTL field data in the Oosterschelde are collected not frequently enough and the data become available only when the bloom is over. High-frequency data at the Brouwersdam give good and timely information about bloom development at the inlet of Lake Grevelingen. However, it is yet unclear whether the location of this sampling point is adequate for prediction of imported blooms. This could not be tested within the ISCHA study, as in 2003 no coastal bloom was imported in the Oosterschelde. We recommend that regular testing of chlorophyll-a concentrations and (possibly) *Phaeocystis* abundance is carried out in and just outside the Oosterschelde estuary, with emphasis on fast processing. These measurements should already start in March detect early blooms, such as the 2003 bloom. For chlorophyll-a measurements simple methods may be used such as fluorimeters or the hand-held spectrometers developed by IVM and provided by Water Insight b.v.

Should we have had this ISCHA system, at what time and by what instrument would the HAB warning been given?

In this study we have used 10 million cells/L *Phaeocystis* or 10 µg/L chlorophyll-a as the criterion for a potentially harmful algal bloom. Table 6.1 gives an overview of the dates when these thresholds are exceeded at different locations in field data, remote sensing data and model data.

Clearly the model is the first to notice the elevated levels. Based on the rise in biomass a warning at march 20th should have been in time to check extra the Wissenkerke and Brouwersdam data (where elevated levels were confirmed at April 1st). Confirmation of elevated levels in the Voordelta came simultaneous from in-situ and remote sensing data.

Table 6.3 Overview of dates when the threshold for 'potentially harmful algal bloom' is exceeded at different locations in field data, remote sensing data and model data.

Parameter	location	field data	remote sensing data	model data
Chlorophyll-a	Voordelta	n.d.	April 13th	c. March 19th
	Oosterschelde	W April 1st	April 13th	W March 20th
Phaeocystis	Voordelta	B April 11th	n.d.	c. March 16th
	Oosterschelde	W April 15th	n.d.	W March 20th

W: station Wissenkerke, B: station Brouwershaven, n.d.: no data, c.: the model data do not represent a specific station, but a heterogeneous area.

Could the warning have been successful?

No mussel mortality due to harmful algal blooms has been observed in the Oosterschelde in 2003, which makes it difficult to assess what would have been the correct day for the warning and whether a warning would have been appropriate at all. The local bloom in 2003 had a peak *Phaeocystis* biomass, observed in field data of 0.2 gC/m^3 , lower than the values in 2001 (c. 0.3 gC/m^3 see Blauw *et al*., 2005 for a comparison of the 2001 and 2003 bloom). It remains yet unclear why the bloom in 2001 caused mass mussel mortality and the bloom in 2003 did not, whereas observed *Phaeocystis* concentrations did not differ much. Possibly, imported blooms (2001) cause more harm than local blooms (2003) because imported blooms experience a sudden change of environmental conditions when they enter the Oosterschelde. This may result in mass algal sedimentation, due to reduced turbulence, increased light intensities and / or fast nutrient depletion. In contrast local blooms are adapted to environmental conditions in the Oosterschelde, so there is no reason for mass algal sedimentation. This hypothesis is supported by the observation that mussel mortality is concentrated at the mouth of the Oosterschelde. Earlier studies (Blauw *et al*., in prep, Hesselmans *et al*., 2005) have shown that the import of the spring *Phaeocystis* bloom in 2001 was simulated correctly with the GEM phytoplankton model. Due to the integration of suspended matter concentrations from MERIS in the model, the GEM phytoplankton model has been considerably improved within the ISCHA-project. Therefore, we are confident that future phytoplankton blooms in the Oosterschelde, both local and imported, can be adequately predicted with the model. The criteria for 'potentially harmful algal bloom' as a threshold of chlorophyll-a and *Phaeocystis* concentrations may need to be reconsidered to prevent false alarms. The comparison of 2001 and 2003 suggests that imported blooms are more harmful than local blooms.

7. SWOT analysis of HAB service

7.1 Introduction

'SWOT' is an acronym that represents Strengths, Weaknesses, Opportunities and Threats. It is a simple tool, often used by organisations for use in strategic planning when releasing a new product on to the market. By building on strengths, reversing weaknesses, maximising opportunities and overcoming threats related to the product, an organisation could optimise its marketing strategy. Strengths and weaknesses are normally internal considerations; opportunities and threats are considerations with more external influence.

The questions that will be answered in this report are:

1. What are the Strengths, Weaknesses, Opportunities and Threats of an integrated HAB early warning service for the Voordelta in comparison to conventional routine monitoring for obtaining information on the short-term development of observed bloom? In view of these Strengths, Weaknesses, Opportunities and Threats, are there any obstacles that could affect the feasibility of an ISCHA service?
2. Does the integrated HAB early warning service for the Voordelta provide a most cost-effective approach for obtaining information on the short-term development of an observed bloom, in view of other methods of obtaining the same information?

Answers to these questions will provide an insight into the technical and economic feasibility for the future development of the ISCHA service, as well as benefits of such a service to society in general.

Question 1 will be answered by means of the SWOT analysis (this chapter).

Question 2 will be answered by means of the cost-benefit analysis (Chapter 8).

Firstly, in Chapter 7.2 the results of a short Internet search are given, to find out if other similar studies have or are being carried out.

7.2 Internet search

The first action taken within WP 5, was to do two searches on the Internet:

Firstly, to find out if others have already performed a SWOT analysis for an integrated HAB early warning service. No such study was found.

And secondly, to investigate if other research groups are developing similar HAB early warning services, as part of the SWOT analysis into Threats. The following results were found:

1. NOAA (US) has developed a system that provides information on the location and extent of red tide blooms in the Gulf of Mexico. An Experimental HAB bulletin alerts subscribers to developing blooms and changes in the location and extent of existing blooms. The HAB Mapping System (HABMapS) provides the position of an identified bloom and data from environmental conditions that may affect the extent or position. Both tools use remote sensing to assess the bloom location and movements. For more information see: http://www.csc.noaa.gov/crs/habf/index.html;

2. The Nansen Environmental and Remote Sensing Center provide a near real-time algal bloom monitoring service for the North Sea and Skagerak (www.nersc.no/HAB/). The service provides near real-time chlorophyll concentration maps based on SeaWiFS, processed by the PML, and Sea Surface Temperature maps based on AVHRR. There is no forecasting provided;
3. In Chile, a national fish farming association, Salmon Chile, has co-founded a pilot scheme with oceanography firm Mariscope Chilena to investigate the feasibility of an operational satellite early warning service for algae blooms using MERIS. At present the scientific feasibility is being investigated but the aim in the future would be to secure delivery of near real-time products within 24 or 48 hours after satellite acquisition for integration into an operational and commercial service (see e.g. http://www.esa.int/esaCP/SEMSO4XLDMD_index_0.html);
4. A new project, currently in the proposal phase, MARCOAST, will integrate the projects ROSES & COASTWATCH, each of which are ESA-funded GMES projects, in which the focus has been on environmental management and monitoring of coastal areas. The aim of MARCOAST is to deliver services such as algal bloom and oil spill early warning services by 2008. IVM will play a small part in MARCOAST and will otherwise remain in contact with the main investigators (Hans J. v.d. Woerd, personal communication).

From these few studies found it can be concluded that although other research groups are developing similar services, the services are not a direct threat to the success of ISCHA, since the above studies are dedicated to different regions (Gulf of Mexico, Chile), do not provide forecasting information or are in an earlier phases of development.

7.3 SWOT analysis

The SWOT analysis has been based on expert knowledge of the ISCHA team members resulting from years of experience using satellite and model data and other more conventional means. The Strengths and Weaknesses are factors that are related to the technical issues of the ISCHA service, whereas the Opportunities and Threats are external factors, for example social aspects of the service. For each of the aspects Strengths, Weaknesses, Opportunities and Threats the most important factors related to remote sensing as a source of information in general and the factors relating to the ISCHA service specifically, have been listed below.

Strengths of RS and an ISCHA service

Strengths

The strengths of the ISCHA forecasting service are directly related to **general** strengths of using and combining the different sources of data within the proposed service, i.e. remote sensing, model and in situ data:

- Unique near real-time information on (possible) HAB occurrence and predicted HAB behaviour;
- RS data can be obtained from regions where no in situ data is available. RS is sometimes the only source of data available;
- Imagery is available at daily frequency;
- Synoptic (area-covering) images;

- The three sources of data complement each other, leading to a better information product than each of the sources alone (1 + 1 + 1 = 5);
- RS data is more cost-effective than in situ data.

The strengths that are **specific** to the ISCHA service are:

- The development of ISCHA is based on methods and techniques developed in previous research projects;
- State-of-the-art algal growth model;
- Information on the dynamics in the surface layer;
- Processing of the RS data up to chlorophyll concentration only requires 3 minutes per image;
- Technical feasibility of service in hindcast mode has been demonstrated;
- Relatively little effort required to make ISCHA operational;
- Interested and well-organized end-user (mariculture sector).

Weaknesses of RS and an ISCHA service

Weaknesses

The **general** weaknesses of a combined data approach, as proposed here, are:

- The RS data retrieval infrastructure in Europe is less than optimal. Much effort needs to be undertaken initially (for each satellite sensor) to set up *data retrieval – processing – dissemination* chain. However this is rapidly changing with the appearance of new sensors and their well-organized helpdesks (e.g. IKONOS, see Tatman *et al*. 2005);
- Limited number of parameters detectable using RS (chlorophyll, TSM, turbidity);
- Inability to detect algal species or toxicity information.

The weaknesses that are **specific** to the ISCHA service are:

- The error in the RS chlorophyll *a* concentrations is approx. 20 – 50%. (see also Peters *et al*., 2005;
- The hindcast case study has been performed using measured data (meteo) and river runoffs. In future, algal bloom forecasts will have to be based on meteorological forecasts and other assumptions (runoff Nieuwe Waterweg and Haringvlietsluizen on the basis of runoff at Lobith);
- The service has not been run in real-time.

The service is directly dependent on characteristics of the RS data. For example, the smallest water body for which ISCHA can be implemented is currently inland large lakes (e.g. Volkerak-Zoommeer) due to the spatial resolution of the sensor.

Opportunities for RS and an ISCHA service

Opportunities

General opportunities for a service, which incorporates RS data, are:

- RS is becoming increasingly accepted as a source of accurate information;
- Availability and use of high spatial and spectral resolution sensors is increasing;

- Optimalisation monitoring strategies being carried out within Rijkswaterstaat. Now is the time to demonstrate an alternative and more efficient way of providing the required information;
- Monitoring commitment is increasing due to new legislation (WFD, European Marine Strategy, OSPAR).

The opportunities that are **specifically** available to the ISCHA service are:

- Changes in global climate could give rise to more frequent and more extensive HABs;
- If ISCHA is shown to work, there is the possibility of developing a similar service for the Volkerak-Zoommeer or other water bodies;
- Possibilities of using ISCHA worldwide (generic application);
- Extension of ISCHA application: use in hindcast mode to help define monitoring programs for specific regions (improve the efficiency of a monitoring program);
- The techniques developed in ISCHA (e.g. data assimilation techniques) can be used to develop similar systems for other parameters (e.g. spreading of sediment plumes).

Threats for RS and an ISCHA service

Threats

General threats to the use of a service which incorporates RS data are:

- There is not yet a complete acceptance of RS data and derived information products as a source of accurate information. To some, in situ data remains the 'ground truth';
- Public authorities not receptive to new technology (internal interests inclined to keep status quo);
- Lack of awareness among potential users of the benefits of the technology;
- Lack of training for interpretation of the value-added information products;
- (Near) real-time availability of RS data;
- Continuity of suitable, optical RS data. ISCHA is based on the analysis of MERIS images. The MERIS instrument is likely to be decommissioned in 2007. The switch to another instrument (e.g. MODIS) will require changes in the analysis software and, more importantly, is likely to lead to an increase in image data costs.

The threats that are **specific** to the ISCHA service are:

- Risk of acceptance. ISCHA is a new service which will (partially) replace conventional, already accepted methods;
- Technical feasibility of running ISCHA operationally in real-time;
- Investment impulse required;
- Uncertain future of the mussel culture industry? After 2007 mussel spat will not be available from the Wadden Sea, potentially disrupting the future of the mussel culture in the Netherlands;
- Other similar services are in development abroad;
- Affordable pricing.

7.4 Summary of SWOT

The following table summarises the results of the SWOT analysis.

Table 7.1 Summary of SWOT analysis results.

Strengths	**Weaknesses**
Unique NRT information on HABs	Suboptimal RS data retrieval infrastructure
RS data globally available & sometimes only source available	Limited number of parameters
Daily image frequency	Lack of species or toxicity information
Synoptic information	RS chlorophyll a concentration error 50-100%
Complimentarity data	Meteorological forecasts required
RS more cost-effective than IS	Service not yet run NRT
Extensive underlying research	Large inland lakes and coasts / seas only
State-of-the-art algal model	
Dynamic information	
Fast processing of RS (3 mins. per image)	
Technically feasible in hindcast mode	
Interested end-user	
Opportunities	**Threats**
RS becoming more accepted	RS not yet accepted by all
Increasing availability high resolution sensors	Receptiveness new technology
Optimalisation of monitoring strategies at RWS	Lack of awareness
New legislation → new monitoring commitment	Lack of training for interpretation
Changes in global climate	NRT availability of RS data
Potential for Volkerak-Zoommeer	Continuity RS data
Generic global application	Risk of acceptance of ISCHA
Extension to monitoring program	Technical feasibility running in NRT
Generic DMI techniques (extension to other parameters)	Investment impulse
	Other similar services under development
	Uncertain future for Dutch mussel growers
	Affordable pricing

7.5 What are the future strategies?

A SWOT matrix is an aid to defining the most important strategies to be taken as a next step in the market introduction of a new product. The theoretical structure of such a matrix is shown in Table 7.2.

The matrix is used here to set out the most important factors that have been identified during the SWOT analysis, for example factors that are a possible threat or weakness to the ISCHA service, and to combine them with the identified strengths and opportunities to counteract the threats or weaknesses. In other words, by building on strengths, reversing weaknesses, maximising opportunities and overcoming threats a successful marketing strategy can be developed.

The format of the matrix has been adapted for this study; the most relevant Strengths, Weaknesses, Opportunities and Threats have been taken from Table 7.1 copied to the second column in Annex II and combined with each other to form a strategy for counteracting a negative threat or weakness, or a strategy for maximising a positive strength or opportunity.

Table 7.2 SWOT matrix.

	Strengths	**Weaknesses**
Opportunities	S-O strategies: Which opportunities are good fit to the strengths?	W-O strategies: Which weaknesses to overcome to pursue opportunities?
Threats	S-T strategies: Which strengths can we use to reduce vulnerability to external threats?	W-T strategies: Defensive plan; how to prevent weaknesses from making ISCHA susceptible to external threats

8. Cost-benefit analysis of HAB service

In this chapter, an analysis is given of the various benefits of the ISCHA service in comparison to the conventional means of in situ measuring. The costs of the ISCHA service will be detailed and compared to the costs of conventional means of obtaining the same information. Firstly, the costs in terms of damage if no information is obtained is given in the next chapter 8.1.

8.1 Socio-economic impact of HABs

Socio-economic impacts of HABs in terms of cost of damage to e.g. tourism and fisheries can be used to compare to the costs of supplying information, either by conventional means of in situ monitoring or using an ISCHA service. In other words, what are the costs if nothing is done, in comparison to the costs for preventing the damage being done in the first place? The aim of this comparison is to find out whether it is worth the investing (in monetary terms) in the operationalisation of a new integrated service for HAB early warning.

Information on the costs of the damage in monetary terms caused by HABs is limited. Only a very few studies have been found:

- In the Scheldt Estuary in 2001, the case study of this project, a toxic algae bloom caused the loss of € 20 million of shellfish production (10 million kilos of mussels were killed, at a value of € 2 / kilo) (Peperzak, 2003). However, an estimated 10 % of this cost would be required for carrying out mitigation measures if an early warning is given, such as removing and transporting the mussels from their fishing grounds in the west tot the east of the Scheldt Estuary, or increasing the O_2 levels at the seabed by means of trawling (Peperzak, personal communication). Therefore, the saving would be minus approximately 10 % of the potential damage cost, in the case of mitigation;
- In the past, HABs have caused significant losses to Chilean aquaculture industry found along its coast. The southern region of Chile has 360 fish farms in the ocean and 40 in freshwater, producing up to 450,000 tonnes of biomass annually. In 1997, Chilean algae blooms caused losses totalling € 10 million (http://www.esa.int/esaEO/SEMSO4XLDMD_planet_2.html);
- A survey by the Belgian Science Policy investigated the socio-economic impact of Phaeocystis blooms, which cause foam on beaches and clog fishing nets (Rousseau *et al*. 2004). The negative economic effects of foam was estimated to be € 3.85 – 5 million, which is 0.4 – 0.6 % of the annual tourism income in Belgium (Persoone *et al*. 1996 in Rousseau *et al*. 2004). An increase of duration or frequency of the bloom during the tourist high season could result in losses estimated up to € 11 million. Although 0.4 – 0.6 % is a small percentage of the annual tourism income; the cost of developing and operating an early warning service such as ISCHA is, in comparison, only a fraction of the cost of the damage.

The costs of damage in terms of ecological value are much more difficult to estimate. In the case of the value of ecological damage following a HAB event, only anecdotal evidence exists (Rousseau *et al.* 2004).

8.2 Benefits of an integrated HAB early warning service

Based on the SWOT analysis above, various general benefits of the use of remote sensing as a source of information can be identified:

- The retrieval of information is on a synoptic and spatially large scale;
- More detail of horizontal parameters and processes is provided;
- Data can be obtained over longer periods in comparison to in situ data, for which data during a limited time only can be obtained, i.e. during surveys;
- Multiple images from different sensors can be used;
- There is the option of near real-time retrieval of data to be used in operational systems;
- A higher continuity is guaranteed in comparison to in situ measurements;
- Data is available in near real-time for forecasting or can be backordered from remote sensing archives to be used in hindcast studies;
- When required, additional parameters can be retrieved from archived data, or improved algorithms can be applied afterwards;
- Relatively cost-effective.

The benefits of the use of conventional (in situ) monitoring, in comparison to remote sensing, are:

- Possibilities of obtaining parameters that cannot measured by remote sensing;
- Detailed depth information;
- More insight into underlying processes;
- Measurements are simple and quick;
- Measurements often provide the most accurate information (i.e. the 'ground truth').

The benefits of an integrated early warning (ISCHA) service, lie in the fact that a combination of remote sensing, model and in situ data is used. Remote sensing can produce near real-time chlorophyll maps showing possible and actual HAB events. No prediction for growth or movement of the HAB can be given by remote sensing data alone, since remote sensing data lack dynamic information. In the case of cloud cover only a partial map (or even no map at all) can be derived from the remote sensing data. Models, on the other hand, are capable of making predictions about HAB growth or movement for any time of day, at any temporal frequency during the period of study. Also, models can be used to 'fill in the gaps' in time, using dedicated data-model integration techniques. In situ data can provide accurate information of the 'ground truth' but cannot give forecasted information. By combining these three sources of data, each with their unique characteristics, and by applying data-model integration techniques, improved predictions can be obtained.

8.3 Cost analysis at WL & IVM

The major sources of costs of an ISCHA service include:

- Set-up costs of models (one-off);
- Image acquisition costs;
- RS Algorithm development (one-off);
- Development of data-model integration techniques (one-off);
- Processing & analysis of imagery / model results;
- Operationalisation of the integrated system (one-off);
- Maintenance of service infrastructure;
- 24-hour standby, if to be operated as a 24-hour service, or
- Standby and / or operation of the service during designated periods (e.g. twice-weekly);
- Production of end-user information product (e.g. HAB bulletin).

The costs will increase with:

- Use of multiple RS images or images from another RS instrument or time interval;
- Increase in RS or model accuracy requirements;
- Increase in number of images to be produced.

The costs of setting up and producing the model and RS data are detailed in a separate document that is confidential. More information can be obtained from the partners.

8.4 Cost analysis at RIKZ

In comparison the major costs of in situ monitoring are:

- Set-up costs (one-off);
- Personnel;
- Calibration of instruments;
- Monitoring program planning;
- Boat time / laboratory time;
- Processing and analysis of data.

The costs will increase with:

- Number of survey sites and sampling stations;
- Number of parameters per station;
- Increase in accuracy requirements;
- Combining multiple instruments.

In this paragraph the costs of undertaking in situ measurements of chlorophyll concentration and / or algal species are specified. A direct comparison is difficult to make with the ISCHA service, because the data sources vary so much in characteristics (e.g. in situ data provide more information on water quality over depth, whereas remote sensing data provides better synoptic information, etc.). Personnel involved in monitoring at Rijkswaterstaat have provided the information.

An indication of the cost is provided in a separate document that is confidential.

8.5 Conclusions

The short internet study that was carried out during this study has shown that although other similar services are being developed, the threat of these is not great due to various reasons: some services are dedicated to other geographic regions, they do not provide forecasting information on HABs or they are in a much earlier phase of development. Due to the latter, it is important to keep the momentum of development of an ISCHA service going, so that ISCHA can become operational before other potential competing services are brought on to the market.

The SWOT analysis has given an overview of the various aspects concerning the future feasibility of the ISCHA service. A summary of these aspects is given in Table 7.1. Strategies for counteracting negative threats or weaknesses or strategies for maximising positive strengths or opportunities have been given in Annex II. Many strategies have been listed and are currently proposed in the follow-up study PHATAFS, which has recently been submitted to NIVR on 30th August 2005. The main conclusion from this analysis is that some obstacles that could affect the feasibility of an ISCHA service have been identified. Some of these obstacles are technical (e.g. running the service in near real-time still has to be automated) but these can be overcome by further research in e.g. PHATAFS. Other obstacles concern the lack of awareness of a remote sensing data-model integrated service, or the threat of receptiveness of new technology. Again, these obstacles can be overcome by focussing on specific strategies such as informing end users through workshops or other consultation sessions such as trade fairs.

The cost-benefit study was designed to find out if the ISCHA service provides the most cost-effective approach for obtaining information on the short-term development of observed blooms in the Voordelta, in view of other methods. In short, it can be concluded that at present the ISCHA service is the only method available for obtaining forecasting information on HAB occurrence and development in the Dutch coastal waters. Satellite or in situ data do not provide dynamic forecasting information and the model data on its own is not verified by satellite and / or in situ data and is therefore not accurate enough for early warning purposes. In terms of whether the ISCHA service is the most cost-effective approach, the answer is simple: it is the *only* method available for early warning of a HAB. Thus, the only alternative would be to not do anything at all, i.e. to not have an early warning service available. The overview of the costs involved if a HAB occurs was given in § 8.1, which included the loss of € 20 million in shellfish production in the Oosterschelde and an estimate of € 3.85 – 5 million in loss of annual tourism income in Belgium. As mentioned, this only includes the loss in economic terms; the loss in terms of ecological value is much more difficult to estimate. As the figures show, the costs of development and operationalisation of an ISCHA service are a fraction of the costs of doing nothing.

The total cost for an ISCHA service for a 3-month period during the bloom period, including set-up and 3 years operation, is estimated at 53 % of the total annual cost for in situ monitoring by Rijkswaterstaat. Although as mentioned, it is difficult to compare these costs directly since each method has its own unique characteristics, it does show that the annual operational costs of ISCHA are comparative with the current Rijkswaterstaat monitoring budget. However, more importantly, the estimated annual cost of the ISCHA service is a very small fraction of the potential loss in monetary terms in shellfish production or tourism income if a HAB occurs in the region of shellfish culture plots or beaches. Therefore, from an economic point of view, the ISCHA service should be commercially viable.

A feasible implementation plan needs to be designed in a follow-up phase to the ISCHA project, e.g. in PHATAFS, to make the service operational. This implementation plan will need to include aspects such as organisation of the service (who will be responsible for the day-to-day running and maintenance of the service, where will the service be located), but also juridical and commercial aspects such as setting up contracts, payment schemes, carrying out advertising and marketing strategies, etc. At present, there are no technical bottlenecks that have been identified that can potentially prevent the successful commercial application of the ISCHA service.

9. Conclusion and Recommendations

Results of the project

In this project we have been able to combine data from in-situ measurements (chlorophyll-a HPLC and *Phaeocystis globosa* counts by flowcytometer), chlorophyll-a maps from remote sensing retrieval and results of complex bio-chemical modelling. These data are very different in the information that is provided and they are very different in temporal and spatial scale and resolution. However, in this project it is demonstrated that when the data from different sources are available at the same time and location they show similar results for phytoplankton. Therefore, the 3 data sources can be used complementary, each filling the gaps in resolution, coverage and confidence of the other. If the information from the different data sources would be contradictory this would not have been possible. In combination all data have provided insight in the evolution of the *Phaeocystis globosa* abundance and chlorophyll-a concentrations in the Oosterschelde and Voordelta in spring 2003. The observations by field monitoring are well reproduced by both the model and the MERIS remote sensing images.

A framework has been set up and tested to use the combination of data sources for an harmful algal blooms early warning service. The output of this service is the production of a so-called 'HAB bulletin' (akin to a weather forecast) twice a week that describes the status of HAB evolution in the previous three days and provides a forecast for the following 5 days. All three pillars of information (in-situ measurements, modelling and remote sensing) are needed to support the HAB bulletin. Satellite or in situ data do not provide dynamic forecasting information and have limited coverage in space and time. The model has been validated for the use as early warning tool only for 2001 and 2003, which is insufficient to rely on model data alone. Furthermore, on cloudless days the resolution of the MERIS data is much better than the model resolution.

Based on the project results we are confident that the envisaged early warning service will provide more adequate information than the presently used method, based on field observations only. However, we have a few recommendations for further improvements of the service:

- Daily field observations for a few years at the mouth of the Oosterschelde of chlorophyll-a and *Phaeocystis* concentrations would enable better model validation and more accurate estimation of threshold concentrations for harmful effects;
- If imported blooms are indeed more harmful than local blooms it may be worthwhile to derive a simple index, indicating the probability of an inflow of the river plume from the Haringvliet into the Oosterschelde estuary, based on wind and tidal conditions;
- Demonstration of the service for a few more years will give better insight in its reliability under different conditions.

Evaluation of the collaboration, including technical issues

The combination of chlorophyll-retrieval from satellite data, modelling capacity and detailed knowledge based on long-term in-situ monitoring within the ISCHA project has provided a very fruitful exchange of ideas and knowledge between the partners. In fact, this project has demonstrated that with this collaboration a unique HAB forecasting system can be build for the Dutch coastal waters.

New patents

This project has not resulted in new patents.

Commercial prospects and follow-up of the project

The main obstacles that could affect the feasibility of an ISCHA service have been identified in a SWOT analysis. Some of these obstacles are technical (e.g. running the service in near real-time still has to be automated) but these can be overcome by further research in relatively small follow on projects like e.g. PHATAFS. Other obstacles concern the lack of awareness of a remote sensing data-model integrated service, or the threat of receptiveness of new technology. Again, these obstacles can be overcome by focussing on specific dissemination strategies such as informing end users through workshops or other consultation sessions such as trade fairs

The cost-benefit study, designed to find out if the ISCHA service provides the most cost-effective approach for obtaining information on the short-term development of HAB in the Voordelta, confirmed that an ISCHA type service is viable and competitive:

Actual Damage for a vulnerable sector:

The overview of the costs involved if a HAB occurs includes the loss of € 20 million in shellfish production in the Oosterschelde, a few million in loss of annual tourism income and the loss in terms of ecological value. The costs are a substantial threat to the sector as a whole and potentially a threat of job loss for individual growers.

Service costs small compared to Damage costs:

The costs of development and operationalisation of an ISCHA service are a very small fraction of the potential loss in monetary terms in shellfish production or tourism income if a HAB occurs in the region of shellfish culture plots or beaches. The ISCHA costs are estimated on half the current additional Rijkswaterstaat monitoring budget for HABs.

Unique forecast capability:

At present the ISCHA service is the only method available for obtaining forecasting information on HAB occurrence and development in the Dutch coastal waters.
At present, there are no technical bottlenecks that have been identified that can potentially prevent the successful commercial application of the ISCHA service. We recommend to start a follow-up phase to the ISCHA project, e.g. in PHATAFS, to finish a feasible implementation plan and to make an investment by all parties to make the service operational.

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Appendix I. HAB Bulletin 24 April 2003

Uitgegeven als voorbeeld binnen het ISCHA project

Conditie: Risicovol

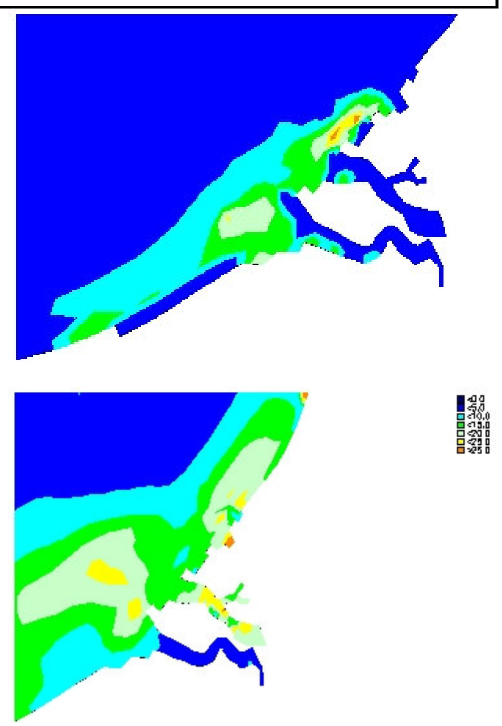
Huidige situatie (23 April 2003)

De huidige situatie van chlorofyl-a concentraties in de Voordelta weergegeven in de twee rechter kaarten. De bovenste kaart is de remote sensing waarneming van 23 april. Hierop is een algenbloei zichtbaar vlak voor Schouwen en de Zuid-Hollandse eilanden en een gebied met relatief hoge concentraties in de monding van de Westerschelde.

De onderste kaart is de modeluitkomst van het algengroeimodel voor 23 april. Hierop zijn verhoogde concentraties zichtbaar voor de kust van Walcheren en in de Oosterschelde.

In beide gevallen is de gemiddelde concentratie van chlorofyl-a in de Voordelta ongeveer 15 mg m^{-3}. Op veel plaatsen is de concentratie hoger dan 10 mg m^{-3} en dus risicovol.

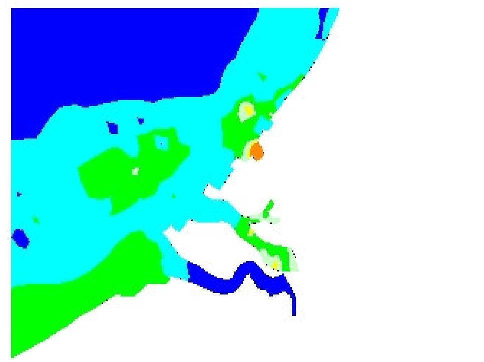
Er zijn geen in situ metingen voorhanden ter vergelijking (deze staan anders in de kaarten geplot).



Voorspelling (29 April 2003)

Volgens de transportvoorspelling (bovenste kaart rechts) zal verhoogde concentratie algen voor Schouwen en de Zuid-Hollandse eilanden zich in Zuid-Westelijke verplaatsen langs de kust en dus verder geen risico meer vormen. De voorspelling van het algengroeimodel (rechtsonder) laat ook zien dat de verhoogde concentraties voor de kust van Walcheren en in de Oosterschelde duidelijk afnemen.

In beide voorspellingen nemen de concentraties chlorofyl-a af in de hele Voordelta, zij het dat er nog steeds gebieden zijn waar de concentratie chlorofyl-a boven de 10 mg m^{-3} uit komt.



Appendix I. Most important SWOT factors and strategy for a future ISCHA service

	Relevant factors influencing ISCHA service	**Strategy**
S-O strategies: which opportunities to focus on	• Monitoring commitment of end-user: • Optimalisation of monitoring strategies at RWS. • New legislation → new monitoring commitment. • Extension to monitoring program.	• Organise a workshop with government and other users (mariculture, tourism). Promote and present tool at workshop. • Develop user-friendly information output, such as the HAB Bulletin, for users through workshop and other consultation sessions.
	• Extension of service and functionalities: • Generic global application. • Generic DMI techniques (potential simple extension to other parameters). • Potential for Volkerak-Zoommeer	• Investigate technical feasibility of generic application for new regions and parameters. • Implement new generic application. • Develop simple, but practical tools for government users and present at workshops, etc.
W-O strategies: which weaknesses can be overcome in short term to pursue opportunities	• Limited number of parameters	• See S-O strategy: investigate and implement extension of service for new parameters.
	• Lack of species information	• Develop data-model integration techniques for combining RS based chlorophyll concentration with simulation results of specific species using algal growth model
	• Suboptimal RS data retrieval infrastructure	• Document *data acquisition – processing – dissemination* procedure in detail, for fast and efficient work flow in future projects
	• RS chlorophyll *a* concentration error	• Further validation of algorithms e.g. in follow-up study to ISCHA

	Relevant factors influencing ISCHA service	**Strategy**
	• Meteorological forecasts required • Service not yet run in NRT	• Follow-up study to ISCHA using meteo forecasts and demonstration of service in NRT
	• Currently, only large inland lakes / seas	• Investigate feasibility of extending service to using high-resolution sensors, e.g. IKONOS & Quickbird
S-T strategies: which strengths can be used to overcome threats	• Strength: • ISCHA can provide unique NRT information on HABS (e.g. dynamic information) • RS data is sometimes only source of data available. • Threat: • RS not yet accepted by all. • Receptiveness new technology • Lack of awareness	• Use added value & uniqueness of service to stimulate awareness & acceptance of end user. • See S-O strategy: organise a workshop with government users. • Promote and present tool at workshop. • Develop user-friendly information output, such as the HAB Bulletin, for users through workshop and other consultation sessions. • Clearly demonstrate benefits and cost saving through workshop and other consultation sessions.
	Strength: • Unique added value of RS data; globally available, synoptic information, daily frequency, complimentarity with IS and model data. Threat: see above	• Use unique added value to stimulate awareness & acceptance of end user (see above).
	Strength: • RS approaches accuracy of IS Threat: see above	• Use improved accuracy of RS to stimulate awareness & acceptance of end user (see above). • Demonstrate accuracy of RS-based in follow-up study to ISCHA.

	Relevant factors influencing ISCHA service	**Strategy**
	• Strength: • Fast processing of RS image • Service in hindcast is technically feasible • Threat: • Technical feasibility running in NRT.	• Technical feasibility in NRT needs to be demonstrated • See W-O strategy: follow-up study to ISCHA using meteo forecasts and demonstration of service in NRT.
W-T strategies: how to prevent weaknesses from making ISCHA susceptible to external threats	• Threat: awareness / acceptance by end users: • RS not yet accepted by all • Risk of acceptance of ISCHA by RWS • Lack of awareness • Receptiveness new technology • Investment impulse	• Stimulate awareness & acceptance • See S-O strategy: organise a workshop with government and other users. • Promote and present tool at workshop. • Develop user-friendly information output, such as the HAB Bulletin, for users through workshop and other consultation sessions.
	• Threat: availability RS data: • NRT availability of RS data • Continuity RS data • Weakness: • Suboptimal RS data infrastructure	• Use well-organised databrokers (e.g. suppliers of IKONOS). • Investigate (high-resolution) products from IKONOS & Quickbird, as well as upcoming sensors, with better data delivery services. • Investigate feasibility of extending service to using IKONOS & Quickbird and other sensors.
	• Threat: • Technical feasibility running in NRT. • Weakness: • Service has not yet been run in NRT.	• See W-O strategy: follow-up study to ISCHA using meteo forecasts and demonstration of service in NRT.

	Relevant factors influencing ISCHA service	**Strategy**
	• Threat: • Other similar services under development? • Weakness: • Limited number of parameters.	• Extend functionality of service (see S – O strategies). • Remain up-to-date with other research projects and services by visiting conferences, literature & internet research etc.
	• Threat: • Uncertain future for Dutch mussel growers	• Focus on other users e.g. tourism sector. Remain in contact with end users by organising workshops, other consultation sessions as well as individual sessions.
	• Threat: • Affordable pricing	• • Ascertain correct pricing is used; develop Business Case Model for pricing. • Develop price list of services and communicate effectively to end users. • Clearly demonstrate benefits and cost saving through workshop, other consultation sessions as well as individual sessions.

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